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RESEARCH ARTICLE

The damages and significant effects of wildfire and stubble burning on vineyards and grapes

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Abstract

The viticulture sector is resolutely combatting the new threats posed by climate change. The impact of climate change, including rising temperatures, increased wind, and drought, has created more favorable conditions for wildfires. Wildfires and stubble burning can inflict substantial damage on vineyards, causing both physical harm and damage from radiant heat. The effect of fires can negatively impact various components of vineyards, such as leaves, shoots, buds, and fruit production organs, and in extreme cases, even lead to the complete destruction of vineyards. The extent of fire damage varies from one vineyard to another, depending on factors such as weather conditions, fire intensity, and the growth stage of the grapevine. At the same time, during fires, smoke carries particulate matter, gases, and volatile phenols that can harm vineyards and affect the chemical composition of grape berries. While the precise physiological effects of smoke exposure on plant growth and development are not fully understood, it is known that smoke can induce necrotic lesions on leaves, hinder photosynthesis, reduce sugar accumulation in fruits, and decrease yield. To assess fire damage, various techniques have been developed, with their application dependent on the severity of the damage. In conclusion, the viticulture sector must continue to develop further research and management strategies to prepare for and combat the threats posed by climate change and wildfires/stubble burning. By doing so, the industry can continue to produce high-quality grapes and wine despite environmental uncertainties.

Keywords

Fire exposure, grapevine physiology, smoke taint, viticulture, yield and quality

Introduction

Terroir is the result of an interaction between climate, soil, landscape characteristics, topography and biodiversity for a particular cultivar within the vineyard and aside from the inherent natural environment, it also encompasses the cultural management of a site. It refers to "the interactions between the identifiable physical and biological environment and applied vitivinicultural practices, providing distinctive characteristics for the products originating from this area" (OIV, 2010). Of these factors, temperature is undoubtedly a strong driving force for grapevine and fruit development (Jones, Davis, 2000; Jones and Alves, 2012). The Mediterranean climate is considered ideal for viticulture. Hence, warm, dry summers are accompanied by cool, wet winters and these combinations of temperature, light and water drive the desirable evolution of berry aroma, colour and flavour in hundreds of grape cultivars (Keller, 2010). That said, grapevines are grown with economic success across a range of climatic zones, resulting in highly diverse wine styles (Van Leeuwen et al., 2004). However, heat, drought, wildfires, excessive rain events and increased pest and disease pressure are posing new challenges for viticulture. Additionally, many viticultural regions are consistently experiencing a general phenological advancement in flowering, veraison and maturity. These trends and emerging challenges have been, at least partially, attributed to a changing climate (Caffarra, Eccel, 2010; Bonnefoy et al., 2013; Malheiro et al., 2013; Cola et al., 2017; Jarvis et al., 2017; Alikadic et al., 2019; Cameron et al., 2022).

Wildfires represent a significant climate issue around the world, with implications for land use and public safety. They are a common occurrence globally, in places such as Australia, South Africa, Mediterranean Europe, and North and South America (Kennison et al., 2007; Hayasaka et al., 2010a; De Vries et al., 2016a; Ristic et al., 2017; Summerson et al., 2020a, 2020b). Unfortunately, climate change effects, such as increases in temperature, winds, and drought, have led to more favorable wildfire conditions (Kennison et al., 2008; Flannigan et al., 2009; Dungey et al., 2011; Kennison et al., 2011a; Cain et al., 2013; CSIRO, 2018; Noestheden et al., 2018a). The incidence and severity of wildfires in fire-prone areas have not only increased in recent years, but fires have begun to affect new regions (Jolly et al., 2015). Each year, nearly 350 million hectares of land are burned across the globe (Royal Botanic Gardens State of the World Plants, 2017). According to the National Oceanic and Atmospheric Administration's 2019 annual Global Climate Report, the nine warmest years on record (i.e., since 1880) have occurred in the last 15 years, with 2016 having the highest global surface temperature to date, being 0.99 °C above average (NOAA, 2019). In the United States, around 7.5 million acres (~3 million hectares) of land have been impacted by wildfires annually since 2011, with 2020 being the worst affected year, during which 10.3 million acres (~4 million hectares) burned; 40% of which was in the state of California (Congressional Research Service, 2021). In Europe, the Mediterranean region (i.e., Portugal, Greece, Italy, Spain, and southern France) is particularly affected by fires. More than 95% of these fires are caused by human activity and many can be attributed to poorly executed use of traditional practices involving intentional burning of shrubs/straw.

Approximately 85% of the half a million hectares of land burned in Europe annually are contained within the Mediterranean region. The majority of fires that take place in the Mediterranean occur between June and October (San-Miguel-Ayanz, 2012), such that the timing of fires poses a serious threat to grape production in those areas. Much of Australia's landscape has the natural propensity to burn, placing it at a significant risk of wildfire danger. As stated by the Bureau of Meteorology, 2019 was Australia's hottest and driest year on record, with average national temperatures surging past the previous record high of 40.3 °C in January 2013, reaching 41.9 °C in December 2019 (Bureau of Meteorology, 2020). During the 2019–2020 fires that occurred in Australia, more than 17 million hectares of land burned, i.e., more than 8 times the area that burned during the historic ”Black Friday” fires in Victoria, Australia in 1939 (Richards et al., 2020). With the frequency of heat waves and droughts predicted to increase, the likelihood of wildfires occurring around the world will also increase (Larsen, 2009). Recent climate research predicts an increase of 15–70% in the number of days of “very high” or “extreme” fire danger by 2050 and a lengthening of the fire season, resulting in more frequent and intense wildfires (Flannigan et al., 2009; CSIRO, 2018; Noestheden et al., 2018b; Climate Council, 2019; Fuentes et al., 2020).

It is widely recognized that the exacerbation of fire incidents can be attributed to climate change, compounded by many factors, including hot, dry, and windy weather conditions; decreased rainfall leading to extended periods of drought; and increased fuel loads which depend on land and fire management practices (Overpeck et al., 1990; Kennison et al., 2008; IPCC, 2019). Many vineyards are located in regions characterized by Mediterranean-type environments with long, hot, dry summers and where both planned controlled burns and unplanned wildfires are prevalent (Sheppard et al., 2009; Kelly et al., 2012; Collins et al., 2014; Krstic et al., 2015). Some of the most prominent wine regions in the world, including those in Australia, Canada, Chile, South Africa, and the United States are experiencing climate pressures, and wildfires have caused serious problems for the wine industry, including crop loss and vineyard damage due to burning and/or smoke exposure (Gillett et al., 2004; Kennison et al., 2011b; Collins et al., 2014; Marangon et al., 2016). As climate change continues, the occurrence of wildfires is expected to increase in frequency and severity, and to affect winemaking regions that have not yet been severely impacted (Albertson et al., 2010; Otero et al., 2017). Parts of southern Europe (in particular, Spain, Italy, and Portugal) have experienced wildfires (especially in 2017–2018) and these regions are predicted to experience more frequent wildfires, with worsening severity in the coming years (Lozano et al., 2016; IPCC, 2019; Alló, Loureiro, 2020). As the incidence of wildfires increases, and periods of drought and fire extend (both in duration and geographical expanse), so too will the fire-related pressures on agricultural production. Furthermore, there are stakeholders with competing interests with regards to fire and land management practices, which can cause secondary problems to arise. For example, unintentional smoke and/or fire damage from prescribed burns, which, depending on their timing, can have detrimental effects on agricultural crops, including grapes for wine production (Ascoli, Bovio; 2013; Otero et al., 2017; AWRI, 2021).

1. Composition of smoke from wildfires/stubble burning

Smoke contains many gases such as nitrogen dioxide (NO_2), methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3), as well as particulate matter including ash, tar, and liquid droplets (Kennison et al., 2009; Bell et al., 2013; Ristic et al., 2016). In addition to this, the pyrolysis of lignin during a fire releases numerous volatile phenols, including guaiacol, 4-methylguaiacol, syringol, 4-ethylphenol, eugenol, 4-methylsyringol, and *p*-, *m*- and *o*-cresols (Kelly et al., 2012; Ristic et al., 2015; De Vries et al., 2016a; Wang, Chambers, 2018). The chemical composition of smoke is greatly influenced by the pyrolytic conditions and the type of fuel present (Kennison et al., 2009). Lignin is composed of three monolingual subunits: p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol, which can decompose to produce various volatile phenols (Kelly et al., 2012; Noestheden et al., 2018a). The ratio of these monolingual subunits varies depending on the plant species; hence the combination of volatiles released from lignin pyrolysis will vary depending on the type of vegetation present (Kostyra, Baryłko-Pikielna, 2006; Kelly et al., 2012). The combustion temperature and oxygen availability also play an important role in releasing volatile phenolic compounds from lignin degradation (Kennison et al., 2009; Kelly et al., 2012). The pyrolysis of lignin is said to begin between 280–290 ◦C; however, as temperatures increase, the composition of lignin pyrolysis products varies, and the release of volatile phenols peaks between 559–650 ◦C (Kelly et al., 2012). Furthermore, different woods vary in their lignin content, with Eucalyptus and Acacia vegetation species typically found in vegetation areas surrounding Australian vineyards containing high amounts of lignin (Nawawi et al., 2017). Regardless of the fuel type, guaiacol and 4-methylguaiacol have been found to represent approximately 20% of the volatile phenolic compounds present in smoke (De Vries et al., 2016b).

2. Uptake and accumulation of smoke volatiles into grapevines add grapes

During a fire event, particulate matter, gases, and volatile phenols from smoke mix with air currents and are transported into the vineyard. The amount of smoke contamination is a function of wind vectors, land topography, temperature gradients, and the vineyards' proximity to the fire (Simos, 2008). Once volatile phenols enter leaves and berries, they are rapidly metabolized into stable glycosidic forms (Pardo-Garcia et al., 2015; De Vries et al., 2016b; Härtl et al., 2017). These glycoconjugate precursors are hydrolyzed during fermentation, releasing them into their volatile forms, where they can impart their aromas into the resulting wine (Parker et al., 2012; Pardo-Garcia et al., 2017). Smoke-derived volatile phenols may enter grapevines via three potential pathways: (i) directly into the berry via diffusion through the waxy cuticle, (ii) uptake into the leaves, and (iii) absorption by the root system after volatile phenols are washed into the soil (Whiting et al., 2007; Krstic et al., 2015; The Australian Wine Research Institute, 2015).

3. Influence of grapevine phenology, grapevine cultivar, and duration of smoke exposure on smoke contamination

3.1. Influence of grapevine phenology and duration of smoke exposure

The timing and duration of smoke exposure greatly influence the extent of volatile phenol uptake by grapevines (Fudge et al., 2011; Ristic et al., 2017). The most sensitive period for smoke contamination in grapevines is seven days post-veraison (Whiting et al., 2007; Department of Primary Industries, 2009; Kennison et al., 2009, 2011b; Fuentes, Tongson, 2017), which unfortunately coincides with wildfires/stubble burning' highest risk of occluding (Fuentes, Tongson, 2017). Studies have demonstrated that exposure of grapevines to smoke during this period results in the highest concentrations of volatile smoke compounds accumulating in grape berries (Kennison et al., 2009, 2011b). Table 1 lists the growth stages of grapevines and the sensitivity to smoke exposure.

Table 1. Grapevine growth stage and the sensitivity to smoke exposure (Kennison et al., 2011a; Brodison, 2013)

Period	Growth Stage	Smoke Uptake Risk
P1	10-cm long shoots	Low
	Flowering	
P2	Pea-sized grape berries	Variable (low to medium)
	Onset of bunch closure	
	Start of veraison to 3 days after onset	
P3	7 days post-veraison to harvest	High

Abbreviations: P1 = Period 1: the stages between "10-cm shoots" to "full bloom", P2 = period 2: the stages between "berries of pea-size" to "the onset of veraison", P3 = period 3: the period between 7 days post-veraison and harvest.

Influence of cultivar on sensory properties following smoke exposure

Several studies have shown that following smoke exposure, the concentrations of volatile phenols in grapes and wine vary depending on the grapevine cultivar. Research conducted by the Centre of Expertise in Smoke Taint Research (CESTR) investigated the effect that grape variety and smoking duration have on the levels of free phenols in grapes and wine following (Cain et al., 2013). Seven different wine grape varieties were picked and then immediately smoked in a purpose-built chamber that used barley straw to generate smoke. Each variety was smoked for different periods: unsmoked (control), one hour (medium smoked), and three hours (high-smoked). Berry and wine samples were then analyzed for levels of free phenols. It was found that increasing the duration of berry smoking led to higher concentrations of free phenols in grapes and wine; however, the level of increase was not proportional to the increase in the time of smoking (Cain et al., 2013). Of the seven different grape varieties, Pinot Gris grape samples were the least affected by the smoking duration and had the least amount of increase in free phenols with an increased amount of smoking time, while Shiraz and Merlot were the most affected and had the greatest increase in free phenols with increased duration of smoking. This shows that different grape varieties vary in their susceptibility and uptake of volatile smoke compounds (Cain et al., 2013), potentially due to differences in berry skin thickness; however, further research is required to determine this. Furthermore, some grape varieties naturally contain low levels of guaiacol and 4- methylguaiacol glycosides in fruit and leaves, including Shiraz, Merlot, and Muscat, which may also explain the differences in volatile phenol concentrations (Kennison et al., 2007; Singh et al., 2011, 2012; Ristic et al., 2015; Härtl et al., 2017). Low levels of volatile phenolic precursors, including phenol, guaiacol, cresols, syringol, methylsyringol, and eugenol, have been detected in numerous grape varieties and may be derived from the degradation of lignified areas of the berries such as the seed (Hayasaka et al., 2010b; Singh et al., 2012).

4. Effect of smoke exposure on grapevine physiology and fruit production, and carry-over of smoke compounds to following years

While smoke exposure on plant physiology and growth is not completely understood, comparisons can be made with studies on the effects of air pollutants as many of the chemicals present in smoke are also components of air pollution (Kennison, 2009; Bell et al., 2013). Smoke contains a complex mixture of gases, including SO2, CO2, NO2, and O3, which have been shown to inhibit photosynthesis and cause leaf necrosis (Calder et al., 2010; Bell et al., 2013; Ristic et al., 2016). Looking at a mixture of three evergreen and three deciduous conifer tree varieties, Calder et al. (2010) found that photosynthesis was reduced by more than 50% following a twenty-minute smoke exposure in five of the six conifer species studied. Evergreen conifers were found to recover faster than deciduous varieties, and no long-term changes were observed in seedling growth or leaf chemistry. Smoke was thought to reduce photosynthetic capacity by reducing stomatal conductance (gs) and impairing biochemical function. In a similar study, the gs CO2 assimilation rate and intercellular CO2 levels of *Chrysanthemoides monilifera* were significantly reduced for 5 h following 1 min smoke exposure (Gilbert et al., 2002). Grapevines are reported to be tolerant to several stressors such as drought, high atmospheric vapor pressure deficit, high irradiance, UV-B radiation, and high temperatures (Bell et al., 2013). Consequently, their resilience may allow them to withstand short periods of smoke exposure without damaging leaf function (Bell et al., 2013). Bell et al. (2013) found that short periods of smoke exposure to Cabernet Franc, Cabernet Sauvignon, Chardonnay, Durif, Pinot Noir, and Syrah grapevine cultivars had only short-term physiological effects on leaf functioning. All cultivars returned to pre-smoke levels of photosynthesis, gs, and transpiration within 48 h. In other research, Kennison et al. (2011b) found that exposure to smoke resulted in reduced yields. In the smoke exposure season (year 1), grapevines exposed to smoke produced an average of 11 kg of fruit per grapevine, compared to control grapevines, which produced an average of 15 kg per grapevine. In the following season (i.e., year 2), no further smoke exposure occurred; however, yields in grapevines originally exposed to smoke yielded approximately 6.4 kg less fruit than control. The reduced fruit yield in the year following smoke exposure was thought to result from reduced photosynthetic capacity (Kennison et al., 2011b). In a previous study, Kennison et al. (2009) found that smoke exposure reduced sugar accumulation in berries and caused necrotic lesions in leaves, which reduced the photosynthetically active leaf area. It was proposed that smoke exposure led to a reduction in photosynthetic capacity, which inhibits berry maturation and ripening (Kennison et al., 2009). Therefore, the reduction in fruit yield may result from altered physiological functioning in the grapevine brought about by smoke exposure (Kennison et al., 2011b). Conversely, Ristic et al. (2016) found few significant differences in berry growth, maturation, and yield between control and smoke-exposed grapevines. Smoke was applied to seven different grapevine cultivars (Chardonnay, Sauvignon Blanc, Pinot Gris, Pinot Noir, Shiraz, Cabernet Sauvignon, and Merlot) for 1 h at approximately 7 days post-veraison. Measurements were then conducted to assess the effects on yield, vegetative growth, and grapevine physiology. Yield was not affected by smoke exposure, and few significant differences were observed between control and smoke-exposed grapes for berry weight and sugar accumulation. Only Shiraz and Pinot Noir grapevines exposed to smoke had lower total soluble solids (TSS) than control (Ristic et al., 2016). One factor that did appear to be affected by smoke exposure was stomatal conductance, and responses varied for the different grape varieties (Ristic et al., 2016). Cabernet Sauvignon, Merlot, Shiraz, Pinot Noir, and Chardonnay displayed significant reductions in gs immediately after smoke exposure. Except in Pinot Noir, the initial reduction in gs was close to 50% of the controls. There was also variation in the time it took the gs for each grapevine variety to recover. Pinot Noir grapevines recovered the fastest, followed by Chardonnay (within 1–3 days), Shiraz (<6 days), Cabernet Sauvignon (6–10 days), and finally Merlot, which was the most sensitive and took the longest to recover (10–15 days). While Shiraz grapevines regained stomatal control after 6 days, measurements taken 17 days later demonstrated that gs was higher in smoked grapevines than control. This variation in response may be due to Shiraz grapevines' anisohydric behavior, which allows them to be less responsive to environmental changes (Ristic et al., 2016). Furthermore, Sauvignon Blanc and Pinot Gris appeared to be unaffected by smoke exposure. It was not surprising that there was variation in gs between grapevine varieties following smoke exposure, as previous studies have also found varietal differences in response to other stressors such as heat stress and/or water deficit (Sepúlveda et al., 1986; During, 1998; Ristic et al., 2016). Calder et al. (2010) also found differences in gs recovery time between conifer species following smoke exposure and noted that plant species could develop tolerance to pollutants that affect photosynthesis. Different plant species may employ various fire resistance strategies and develop tolerance mechanisms to avoid smoke exposure's detrimental effects (Calder et al., 2010). Fuel type may also influence the physiological response of grapevines to smoke (Bell et al., 2013). As smoke composition can differ depending on the fuel sources present, the varying emissions produced may result in different leaf-level responses amongst plants (Bell et al., 2013). Bell et al. (2013) found grapevines were more sensitive to smoke generated from burning leaf litter from Coast Live Oak compared with Tasmanian Bluegum. This research only used single fuel types; however, results may vary if a mixture of fuel sources are used as occurs in wildfires (Bell et al., 2013). Furthermore, the duration of smoke exposure, the concentration of smoke components, and other plant stressors such as nutrient status, drought, and high temperatures may also affect the physiological response and recovery of grapevines following smoke exposure (Bell et al., 2013; Simos, 2008). For example, research by Summerson et al. (2020a) found that the intensity of smoke exposure affected the extent of stomatal closure and hence gs in Cabernet Sauvignon grapevines. Further studies should, therefore, take all variables into account (Bell et al., 2013). Smoke taint compounds do not appear to carry over to the following season (Department of Primary Industries, 2009; Kennison, 2009). Grapevines repeatedly exposed to smoke in one year have been shown not to carry over volatile phenols and their metabolites into subsequent years, when no further smoke exposure occurred (Kennison, 2009; Kennison et al., 2011b).

5. Management of fire-damaged grapevines

During a fire, grapevines may be physically damaged by flames and/or by radiant heat from the fire. Often both the physical damage and radiant heat damage may appear similar and range from slight scorching of leaves to complete destruction of the grapevine. Fire may damage all grapevine structures and result in injury or death of leaves, leaf petioles, buds on canes and shoots (including latent buds), flowering and fruit production organelles and the vascular system. Depending on the degree of damage, grapevines may recover to full fruit production or be irrevocably damaged and die. At any given vineyard site, fire damage is often inconsistent and highly variable. Weather conditions, fire ferocity and the growth stage can all contribute to the degree of grapevine damage. A limited number of investigations of grapevines following fire have focused on assessing the immediate damage and applying pruning treatments. Useful techniques for assessment of grapevines after fire damage include (Brodison, 2013):

- *Visual grapevine assessment*: To be conducted immediately after the fire and include assessing damage that may be 'nil' (no visible damage), 'low' (such as minor leaf scorch), 'medium' (damage to leaves, inflorescence/fruit) or 'high' (severe scorching and damage to all plant parts from contact with flames). Visual assessment should be based on individual varieties and record the location of grapevine damage within a block.

- *Cambium assessment*: A small knife incision in the trunk can be made to investigate the colour of the cambium tissue. Healthy tissue is moist and green, damaged tissue is dry and pale, while dead tissue is dry and brown (Whiting, 2011).
- *Trunk staining*: This was investigated by Scarlett et al. (2011) where transect sections of trunk are cut and stained with methylene blue. If the segment is bright blue then the tissue is 'viable', if the trunk segment is a dirty blue or brown then the tissue is 'unviable'. This method is destructive to the grapevines, however, provides an immediate indication of the fire's effect.
- *Bud dissection*: Can provide indication of viability and potential fruitfulness of buds within cane material. With a microscope, dissection of buds indicates whether they are alive (green) or dead (brown/black). Dissection is best conducted prior to winter pruning in order to provide information on the optimal number of budAfter comprehensive assessment of grapevines after fire damage, a number of management techniques can be employed to aid recovery. Techniques depend on the severity of damage that includes (Brodison, 2013): s to retain on the grapevine and their position within the canopy.
- *No damage*: Continue grapevine management as usual, paying attention to grapevine health, and apply additional irrigation to grapevines that show heat stress symptoms from the fire.
- *Low damage*: Continue grapevine management as usual, applying additional irrigation after the fire, and consider a pruning strategy to investigate (bud dissection) and retain viable buds during grapevine dormancy.
- *Medium damage*: Apply irrigation as soon as possible after fire. Monitor grapevines for stress and further signs of decline, and investigate health status of cambium material in trunks. Investigate bud fruitfulness prior to dormant pruning as additional buds may need to be retained to encourage growth and fruitfulness. Grapevine fruitfulness may be impacted in the following season and additional training of replacement grapevine shoots, arising from the crown and cordon, may be required.
- *High damage*: Likelihood of survival is low. Grapevines should be irrigated to encourage recovery; however destructive methods of survival assessment (trunk staining) would provide an immediate indication of viability. Grapevines may be minimally pruned to encourage shoot growth in viable buds and further assessed for survival in the following season. Replanting or grafting of unproductive grapevines may be required.

When fires occur near wine regions, smoke can drift into vineyards and, depending on the timing and duration of smoke exposure, can taint grapes, and therefore wine (Kennison et al., 2009, 2011b; Krstic et al., 2015). There are several techniques that growers can employ in-field to reduce contamination of smoke. Table 2 lists a number of these techniques. Preventative methods that have been explored included the following: washing grapevines/grapes, partial leaf removal and the application of agricultural sprays. Promising research by van der Hulst et al. (2019), Rogiers et al. (2020) and Favell et al. (2019) has found that foliar applications of kaolin or biofilm composed from phospholipids may provide some protection from the uptake of smoke compounds.

Conclusions

The viticulture sector is currently facing significant challenges in a period where factors such as rising temperatures, increased wind, and drought, driven by climate change, are amplifying the risk of wildfires. Wildfires and stubble burning can inflict substantial damage upon vineyards, impacting everything from leaves to fruit production organs. Harmful substances carried by smoke can disrupt the chemical composition of grape berries. While the full effects of smoke on plant growth remain not completely understood, it has the potential to reduce fruit yield. The extent of wildfire/stubble burning damage varies based on weather conditions, fire intensity, and the grapevine's growth stage. Assessment techniques have been developed, and research is ongoing to explore preventive methods, like agricultural sprays, to reduce smoke contamination. The industry must continue to develop research and management strategies to safeguard sustainable productivity while confronting these challenges posed by climate change and wildfires/stubble burning.

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