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The Potential Effects of Plant-to-Plant Interactions on Wine Aroma: a Review

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THE POTENTIAL EFFECTS OF PLANT-TO-PLANT INTERACTIONS ON WINE AROMA: A REVIEW

by

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HEADING 1

INTRODUCTION

Plants produce Plant Secondary Metabolites (PSMs) for the role of defense. PSMs include over 300,000 molecules and are categorized as either phenolics, terpenoids, alkaloids, and others (Han 2019). These molecules play important roles in defense against abiotic stress (water, temperature, light, and salt) and biotic stress (fungi, viruses, bacteria, feeding herbivores, and weed competition) (Igny and Wim 2017). The Latin word ‘turpentine,’ a liquid extract from pine trees, is the origin for the term terpene and is associated with odoriferous compounds. Terpenes are in high concentrations in many higher plants (Ninkuu et al. 2021). In the plant, they are distributed through the leaves, flowers, stems, fruit, and roots depending on the species and specific compound (Ingy and Wim 2017). Terpenes are a wide class of compounds ranging from 5 to 40 compound units. The largest class of terpenes is the monoterpenes, and this class of compounds contributes to aromatic profile more than other terpene classes. Sesquiterpenes are the next largest class of terpenes known to contribute to aroma. Monocotyledonous and dicotyledonous angiosperms, fungi, bacteria, and gymnosperms contain monoterpenes. In many flower and fruit crops monoterpenes largely account for the aromatic profiles of those crops (Ninkuu et al. 2021). While PSMs have developed from an evolutionary need for defense in plants, humans have recognized and utilized plants for their aroma.

HEADING 2

PLANT SECONDARY METABOLITES

Wine grapes are strongly regarded for their volatile organic compound profiles. Wine aromas develop or derive terpenes from the following four categories: from the grape, enzymes involved in crushing of the grapes, products of grape fermentation, or products of the wine's maturation (Marais 1983). Earlier work on terpenes distinguished Muscat (Muscat d' Alexandrie, Morio Muscat, and Muscat blanc) and Muscat-related varieties (Weisser Riesling, Bukettraube, Gewürztraminer, Fernão pires, and Scheurebe) from other wines for their higher concentrations of terpenes. Depending on the specific molecule, monoterpenes most commonly have floral, rose-like, camphoraceous, green, or herbaceous (Marais 1983) aromas. For example, linalool, geraniol, and rose oxides epitomize Gewürztraminer wines (Robinson et al., 2014). Wine grapes not only vary in their volatile organic compound profile due to variety, but also due to terroir, which is a complex and multifaceted concept.

The concept of terroir has been an important aspect of the winemaking world since Roman Times. As proposed by Moran (2006), there are six important facets of terroir: territorial, agronomic, vinification, identity, legality, and promotion. It is a goal of modern research to distinguish these six important facets. The natural factors that fit into the territorial category include geology, soil, climate, topography, and the interdependence of these factors. The agronomic factors include plant physiology, adaptations of the vine to the environment, root growth, plant response to the soil in which it grows, canopy architecture, and others. The winemaker and winegrower, themselves, play a large role in managing the natural aspects of terroir, and many definitions of terroir incorporate the human factor (Mouton, 2006). Identity, legality, and promotion are important elements of terroir from a historical perspective (e.g. Wine and legal law in different regions, advertising, and cultural traditions). There are other human elements of terroir that are lesser considered. Variety selection is an important human factor involved in terroir since the largest factor in wine aromatic profile is due to variety. Cultural practices can also determine how a grape is grown. Understanding how climate can affect grape varieties can vary by not only what terpenes develop in the grapes, but the concentration of terpenes found in grapes and wines. Sauvignon blanc from different growing regions have significantly different concentrations of linalool, citronellol, and geraniol; however, geraniol is not as affected. Warmer regions (USA, Australia, and South Africa) have lower levels of citronellol, linalool, and geraniol compared to the cooler regions (New Zealand and France) (Benkwitz et al. 2012).

HEADING 3

VOLATILE COMPOUNDS IN WINE GRAPES

Cultural practices, such as deciding when to harvest, could affect terpene levels since ripe fruit has higher concentrations of terpenes (Marais 1983). The findings from many viticultural trials have concluded that exposure of berries to sunlight through leaf plucking, shading or canopy management appears to increase both free and bound monoterpenes. A higher concentration of monoterpenes and their glycosides are associated with improvements in grape composition due to vine water deficit and crop thinning (González-Barreiro et al. 2015, Robinson et al. 2014a). Research as mentioned shows cultivar selection, climate, and management practices clearly influence grape aromatic profile. While most varietals have similar profiles with slight variations coming from terroir and cultural elements, terroir can exhibit a more abstract form. For example, some wines have been referred to as "garrique" which is the Mediterranean term referring to hillside shrubs. In wine terminology it references herbal characteristics especially lavender, thyme, and rosemary (Gabay 2018). Correspondingly, Australian red wines have long been noted for their "eucalyptus" aroma, but with little explanation or qualification of this description. More recent research has looked for an ecological perspective to explain these variations in regional differences in aromatic profiles especially regarding terpene content.

HEADING 4

EUCALYPTUS SOURCE AROMA DETERMINATION

Eucalyptus is a genus of plant native to Australia. It has gained popularity for timber and has been utilized for furniture, farming tools, transmission poles, railroad sleepers, fuelwood, honey, pulp, rayon paper, fiberboard, plywood, essential oils, plant growth regulators, tannin extracts, industrial chemical additives, adhesives, fodder additives, and fabrics. Citronellol, menthol, thymol, and roseol obtained after further processing of Eucalyptus oil enhance the aroma in throat lozenges, oil balms, cooling ointments, cold ointments, toothpaste, perfume, and soaps (Davidson 1993).

There are 900 species of Eucalyptus, and only 20 species contain high concentrations of essential oil, especially 1,8-cineole, also known as eucalyptol (ABARES 2018). By 1993, North America had 110,00 ha planted, Uruguay had 160,000 ha planted, and Australia had 75,000 ha planted (Davidson 1993). All three of these countries also had high anecdotal rates of “eucalyptus” aromas in their red wine profiles. “Eucalyptus” is also an aroma descriptor used in wine terminology associated with the monoterpene 1,8--cineole. In Californian Merlot, recognition thresholds estimated at 1.1 µg/L and associate with descriptors of “fresh,” “cool,” “medicinal,” and “camphor” (Herve et al. 2003). Recognition thresholds estimated at 1.3 µg/L in Tannat wine (Fariña et al. 2005). Proximity to Eucalyptus trees was proposed to explain “eucalyptus” aroma in wine a mechanism for aerial transfer of 1,8-cineole. Fariña et al. (2005) proposed a different source of 1,8-cineole for Tannat wines produced in Uruguay in areas “mostly located in the region of the southern part of Uruguay away from the influence of Eucalyptus trees.” In these Tannat grapes, concentrations of 1,8-cineole increased parallel to sugar content prior to harvest with final levels of approximately 12 µg/kg. This study showed that 1,8-cineole forms in grapes without the influence of Eucalyptus. In addition, fermentation studies showed that 1,8-cineole can be formed from the limonene and α-terpineol still at very small levels (Fariña et al. 2005)..

Australia has high anecdotal occurrences of Eucalyptus aromas in wines from its regions especially compared to any other wine regions. When 30 Cabernet sauvignon wines from 10 unique Australian geographical indications (GIs) were analyzed, Langhorne Creek and Clare Valley had high amounts of eucalyptol, while Wrattonbully showed moderate amounts compared to the other GIs (Robinson et al. 2012). There was a high degree of variability in 1,8-cineole between GIs. Capone et al. (2011) found that of 146 commercially available Australian red wines 40% of those wines tested positive for 1,8-cineole concentrations at or above established recognition thresholds. Shiraz and Cabernet sauvignon were two varieties that tested in the highest concentration category, with 5 to 20 μg/L. These varieties have long fermentations on the skins of grapes. The observation that concentrations of 1,8-cineole may increase with days of skin contact for red wines could explain the high concentrations of 1,8-cineole in Shiraz and Cabernet sauvignon. The highest concentrations of 1,8-cineole are in the grape berry skin with average concentrations in the skin at 1.31 ng/berry and the pulp only at 0.36 ng/berry (Capone et al. 2012). Experiments in Western Australia and Victoria were the first of their kind to show that 1,8-cineole decreased in concentration as the harvest location increased in distance from a Eucalyptus tree line bordering the vineyard. According to maps showing the distributions of Eucalypt forests in Australia, concentrated Eucalypt open forests overlap with wine growing regions such as Western Australia and Victoria (ABARES 2018). Concentrations of 1,8-cineole were considered almost negligible (0.4 μg/L) until rows were at least 230 m from the tree line. A distance of 50 m was sufficient to reduce 1,8-cineole in harvested fruit. In a site located in

Coonawarra, two successive vintages found that wines located near well-established Eucalyptus trees proved to have obvious “eucalyptus” character with measurable 1,8-cineole. In this study where vines located within 5 m of Eucalyptus trees, grape skins contained four times as much 1,8-cineole compared to the pulp. This again shows wines fermented on the skin are more likely to contain high 1,8-cineole levels. Noted vintage variations, which may include the following: vigor of the canopy, degree of grape exposure, position of berries, and size of the berries. There was a similar distance from tree trend when analyzing concentration in grape leaves and stems. This trend was similar between 2 vintages, with variation in concentration between vintages. This study also confirmed the airborne transmission of 1,8-cineole by using polyethylene airborne traps. Traps accumulate between 0.1 to 2.3 μg/trap. Capone et al. (2012) showed that there was an obvious correlation between proximity to Eucalyptus trees and the concentration of 1,8-cineole in finished wine. This research provides options for vineyard management by considering where vineyards are planted in proximity to tree lines. Distance from Eucalyptus tree lines allows for controlling the finished wine’s aroma profile despite the inability to control airborne drift of monoterpenes.

Fermentation results from Capone et al. (2012) could be utilized to methodically control 1,8-cineole levels through common winemaking techniques, and results confirmed that higher amounts of 1,8-cineole are extracted from grape skins, and levels are increased when wines are fermented on the skins for longer amounts of time. Correspondingly, lightly pressed rosé wines would have less skin contact compared to hard pressed rosé wines. When the fruit was separated from any material other than grape (MOG), concentrations were significantly lower than when fermented with the grape leaves and stems. Specifically, 1,8-cineole levels were higher in grape stems compared to leaves, and notably higher compared to grapes. During this study, researchers found physical debris from Eucalyptus trees (stems, twigs, and leaves) in the grapevine canopy. They determined that only 67.5 grams of debris in 1 ton of grapes would result in 210 µg/L of 1,8-cineole. To further test the effects of Eucalyptus debris, when material from Eucalyptus trees such as bark and leaves are added to crushed grapes prior to fermentation, the finished wine has 1,8-cineole levels up to approximately 30 µg/L. They did not clarify how much material was added at crush. Even so, this response indicates that the largest source of 1,8-cineole would be contributed to MOG directly sourced from Eucalyptus trees. This material could naturally contaminate the vineyard by wind spreading material from nearby trees. In Australia, Eucalyptus sheds its bark during December which is just prior to grape harvest, which starts in February (Grootemaat et al. 2017).

Eucalyptus trees have the potential to spread debris physically in direct relation to their proximity to grapevines, as well as drifting their volatile organic compounds. Sorting out MOG prior to crushing, cleaning fruit, or carefully harvesting by hand, could help control 1,8-cineole levels. The research by Capone et al. in 2012 was the first study confirming the volatile organic compound drift. This research acknowledges that there are several sources of 1,8-cineole, and to varying concentration. This study provides insight at critical points where MOG can affect the aroma of the finished wine. With methods for controlling 1,8-cineole levels, winemakers can consider what levels of this aroma consumers can accept for their wines and manipulate these levels to target consumer preference. Tasting panels have studied the thresholds at which 1,8-cineole is considered an enjoyable aroma or taint. In these panels, the consumer rejection threshold using spiked samples with 1,8-cineole found 27.5 µ/L to be the critical rejection threshold. Consumers accepted moderate to no 1,8-cineole, and there was no apparent gender, age, experience level preferences, so acceptability was concluded to be broad (Saliba, Bullock, &

Hardie, 2009). Knowing preferences of consumers can help guide winemakers' decisions about how to include or exclude possible contamination by Eucalyptus trees. Common wine making techniques such as press fractioning to control skin contact, separating fruit from any possible MOG, and destemming can all control 1,8-cineole levels in wine from vineyards near Eucalyptus trees.

Additional research is needed to determine variation in eucalyptol concentration by Eucalyptus species. There are variations in the species of Eucalyptus when considering essential oils extracted from Eucalypt leaves. With variation found between vineyards and GIs in previous studies, understanding species variation in terpene concentrations could further explain the regional variation found in wine. *Eucalyptus cinerea*, *E. sideroxylon*, and *E. icostata* contain the highest concentrations of 1,8-cineole known within the genus, at approximately 70% of the essential oils extracted from their leaves. *Eucalyptus aidenii*, *E. ehmannii*, *E. stringens*, and *E. eucoxylon*, had notably high concentrations (approximately 43%). Of the 8 species known for high concentrations of 1,8-cineole, *E. dorata* had the lowest concentrations in comparison to the other species at only 4.2%. There is potential for other volatile organic compounds to also impart aroma differences on wine due to drift or as MOG, but at this time 1,8-cineole dominates the scientific discussion. *While at smaller concentrations*, *Eucalyptus* contains many other terpenes. In Eucalyptus, α-Pinene had values ranging from 1.02 to 2.0%, α-Terpineol from 0.810 to 3.0%, and limonene from 0.4% to 4.4% (Elaissi et al. 2012). These concentrations are lower relative to 1,8-cineole; however, it is important to consider the importance of aroma in wine. Spearmint aromas are present with detectable concentrations of p-Cymene (Dunlevy et al. 2009), and α-Pinene contributes floral, lilac, and pine (Matarese et al. 2013). Limonene and α-Terpineol have the potential to form additional 1,8-cineole as discussed above, but in their original form limonene would contribute citrus, flowery, and green aromas (Jiang and Zhang 2010) and α-terpineol contributing floral, lilac, and pine (Black et al. 2015).

With “eucalyptus” aroma now attributed mostly to neighboring Eucalyptus trees, this ecological characteristic in specific wine regions has the capacity to play a large role in wine’s aroma profile. This idea adds a dimension to the terroir of wine and is a unique identifying factor for many Australian red wines, especially Shiraz and Cabernet sauvignon. Understanding the true sources of “eucalyptus” aromas in red wines, has prompted interest of other plants and VOCs in future and current research topics in ecology, viticulture, and enology. Other unique terpenes have been attributed to MOG caused by *Eucalyptus* species, and other native flora are being considered to contribute to distinctive aromas for wine grapes. Some additional species are native to vineyard landscapes such as weed species like *Artemisia verlotiorum*, or neighboring plants like wild blackberry (*Rubus* spp.). Other crops of interest are grown in nearby fields such as lavender-related species *(Lavandula)*, and hemp (*Cannabis sativa* L.).

Black pepper can be a flavor which describes wine, especially Australian Shiraz. Wood et al. (2008) found that rotundone was the sesquiterpene responsible for the black pepper aroma in wine. “Black pepper flavor” is used to describe aromas associated with other plants such as herbs, spices, and even weeds. Concentrations of rotundone measured at 2025 µg/kg for black pepper and 1200 µg/kg for white pepper, but only 0.15 µg/kg Shiraz wine and 0.62 µg/kg in Shiraz grapes. Most notably of the other plants analyzed, nut grass (*Cyperus rotundus*) measured at 920 µg/kg rotundone, majoram (*Origanum majorana*) measured at 208~~,~~ µg/kg, and rosemary (*Rosmarinus officinalis*) measured at 86 µg/kg. On the lower end, yet considerably higher than wine and grapes were saltbush (*Atriplex cinerea*) at 37µg/kg, geranium (P*elargonium alchemilloides*) at 25 µg/kg, thyme (*Thymus vulgaris*) at 5 µg/kg, basil (O*cimum basilicum*) at 4 µg/kg, and oregano (*Origanum vulgare*) at 1 µg/kg. Wood et al. (2008) also identified that sensory thresholds for rotundone in water and in red wine. They concluded that 20 to 25% of the panelist were unable to detect rotundone in either solution at the concentration of 4000 ng/L. The lowest concentration of rotundone detected by the panelist was the lowest tested concentration at 0.4 ng/L. When considering odor activity values (OAV is ratio of concentration to odor threshold value of the compound) in black or white peppercorn, the odor activity value was 50,000 to 250,000 with methods used by Jagella and Grosch (1999). In comparison, OVA values measured at 1,300 to 3,000 for linalool and 810 to 1,800 for limonene.

Zhang et al. (2015) assessed Australian vineyards for markers that could correlate to rotundone concentrations. They found that bunch zone air temperature and daily solar exposure negatively correlated with final rotundone concentrations, and vine water balance negatively correlated. Generally, the highest rotundone concentrations were found in grapes grown in cool and wet environments. Apart from climatic variation between different sites and vintages, rotundone concentrations could be influenced by ecological factors as well. Capone el at. (2012) analyzed rotundone in the MOG study as well. Results showed that grape stems (12.4 ± 0.5 µg/kg) contained higher concentrations of rotundone compared to leaves (4.8 ± 2.7 µg/kg) when sampled 1 row away from Eucalyptus trees surrounding the vineyard site. Leaves and stems contained lower concentrations when sampled further from the Eucalyptus trees (row 20) at 0.9 ± 0.3 µg/kg for leaves and 0.65 ± 0.5 µg/kg for stems. Differences in processing methods affected rotundone concentrations as well. When grapes were picked, crushed, destemmed, and pressed skin contact time was minimized, final rotundone concentrations were the lowest at 8.5 ng/L. When researchers harvested grape clusters in a method to exclude any MOG, but still fermented after being crushed and destemmed, rotundone concentrations were at 34.5 to 38 ng/L. After grape clusters were fermented with the skins, stems, and leaves, this method produced the highest rotundone concentrations, 205.5 to 221 ng/L. Finally, additions of leaves and bark from Eucalyptus into crushed and destemmed grapes, increased rotundone concentrations to 54 ng/L. This study concluded that stems contribute the largest contribution to rotundone concentrations, and winemaking methods such as destemming would decrease rotundone concentrations. Skin contact during fermentation also increased rotundone concentrations to a lower extent. Compared to 1,8-cineole, winegrowers could limit rotundone concentration by limiting exposure to Eucalyptus; however, its source is mainly attributed to concentrations found in the skin and stems of grapes (Capone et al. 2012).

HEADING 5

OTHER SOURCES OF TERPENE DRIFT

After Capone et al. (2012), many other studies have questioned the potential of other native flora to affect 1,8-cineole levels as well as other terpenes. In France, Poitou et al. (2017) tested terpene levels in red wines from various growing regions. Samples revealed a median concentration of 1,8-cineole at 0.28 µg/L for all samples. Three wines, all Cabernet sauvignon with a small proportion of Merlot, from the same vineyard in the Paulliac appellation of Bordeaux, France had high levels compared to the median at 2.24, 2.38, and 1.04 µg/L, and were noted to have distinct minty and herbal aromas. These wines also had notably high concentrations of α-thujone at 2.62, 2.76, and 1.43 µg/L. No other wines had detectable concentrations of α-thujone. Researchers found *Artemisia verlotiorum*, commonly referred to as Chinese mugwort, populating this vineyard site. Crushed *A. verlotiorum* leaves contained 1,8-cineole levels of 345 ± 9 mg/kg fresh weight. *Artemisia verlotiorum* contained two other compounds in concentrations, α-thujone (587 ± 26 mg/kg) and β-thujone (176 ± 9 mg/kg). There was no evidence of major sesquiterpenes. This conclusion led Poitou et al. (2017) to conclude 1,8-cineole and α-thujone could spread to grape vines by aerial transmission since sesquiterpenes were likely to be detected if MOG was the major source. Of the 18,000 reported occurrences of *A. verlotiorum*, 9,200 have been reported in France (GBIF 2021). *Artemesia verlotiorum* was first described in 1873 in Grenoble, France and then again in 1877 in Clermont-Ferrand, France (Vernin 2000). Wild *A. verlotiorum* collected in Côte d'Azur, France contained high amounts of monoterpenes. The extracted essential oil’s highest monoterpene concentrations were α-thujone (47%), 1,8-cineole (21%), and β-thujone (10%). All other compounds were notably lower (Vernin 2000). *Artemisia verlotiorum* is also found throughout Italy with 406 occurrences concentrating along borders of France in the Wine Regions of the Piedmont Valle D'Aosta, and Liguria as well as Tuscany, (GBIF 2021). When essential oil concentrations were studied in A. *verlotiorum* collected in Pisa, Italy in the region of Tuscany each month of the year, 1,8-cineole (32.2%), camphor (8.3%), and b-thujone (14.7%) were the highest in September and had relatively similar concentrations in August and October. Additionally, A. *verlotiorum*'s essential oil in thein the highest concentration was 1,8-cineole throughout the year with the only exception in November (Chericoni et al. 2003). *Artemisia verlotiorum* is one additional species to Eucalyptus that shows a strong potential to influence the grape aromatic profile although it has been minimally studied.

In Northern Italy, *Rubus laciniata* L. (blackberry) is a native species surrounding vineyards. To test if blackberries have the potential for effecting aromatic profiles of nearby grape, one study utilized Pinot noir vines planted in pots with or without blackberry plants. When vines were three years old, the grape berries were analyzed at harvest. Free geranic acid was 250% higher in Pinot noir grapes that were co-planted with blackberry plants. Free epoxylinalool was 271% higher. Bound geranic acid, epoxylinalool, linalool oxide, exo-2-hydroxycineole, α-terpineol, and epoxylinalol-2 were all found at significantly higher rates in treated vines (Tomasi et al. 2017). Plants have the potential to communicate below the ground by emitting VOCs through their roots or above ground through flowers and leaves (Ninkovic et al. 2020), and this could explain how co-potted blackberry plants could affect monoterpene levels in Pinot noir. Monoterpenes are important in red wines such as Pinot noir for their interactions with other aroma compounds. In Pinot noir from Central Otago, monoterpene levels of linalool, nerol, geraniol, β-citronellol, and α-terpineol, were all detected lower than the odor thresholds previously established. However, when monoterpenes were omitted from wines, there was an increased perception of lactic, rose, fruit jam, and chocolate, but a decrease in ash aroma. In Pinot noir, monoterpenes could affect a wine's aroma profile by indirectly amplifying or repressing other aromas (Rutan et al. 2014).

Several species in the *Lavandula* genus are produced for essential oils. While concentrations of volatile organic compounds vary among species, linalool and linalyl acetate are the main constituents. Borneol, α-terpineol, terpinene-4-ol, lavandulol acetate, 1,8-cineole, and camphor have also been found in *Lavandula* species (Détár et al. 2020). Lavandulol and lavandulol acetate contribute an herbal-rosy aroma. Species in the genus of *Lavandula* are native to the Mediterranean and grow best in well-drained, fertile and basic soil in full sun (Prusinowska 2014). *Lavandula* spp. are commonly referred to as lavender, and occasionally lavandin (Dutch Lavander). Castilla-La Mancha produces 70% of lavender in all of Spain (6352 tons in 2011) along with 4.44 million tons of wine annually and is one of the world's top three producers (FAO 2019) at 73.47% of the wine volume in Spain (Jeffs 2006). Quite often, the vineyards are growing directly next to lavender fields. Lavender contains high concentrations of volatile terpene compounds: linalool, α-terpineol, 4-terpineol, and camphor. Martínez-Gil et al. (2013) questioned how lavender could affect grape aroma profiles similar to Eucalyptus's effect as discussed by Capone et al. (2012). Martínez-Gil et al. (2013) considered the effects of the lavandin hydrolats (distilled water obtained from steam distillation of essential oils) from several perspectives. This idea targets how wines produced from certain regions could further define their identity based on crops nearby whether it be the native flora or other important crops to the region. Furthermore, lavandin hydrolats contain water soluble volatile compounds, and are normally the portion that is discarded in essential oil production. Martínez-Gil et al. (2013) proposes that this part could potentially be used as a pesticide alternative. No studies have been done to test terpene drift in Lavandula on a scale similar to Eucalyptus. However, in their experiments, Martínez-Gil et al. 2013 applied lavandin hydrolats to Petit Verdot grape vines in the field, and they found a potential to alter the aroma profile of the wines by increasing limonene and nerol by the end of alcohol fermentation (Martínez-Gil et al. 2013). This would result in an aroma profile with increases of fruity and citrus and of geranium oil (Jiang and Zhang 2010; Guth 1997).

With the rise of industrial hemp (*Cannabis sativa* L.) production after the legalization of hemp in the 2014 Farm Bill, production in the United States has increased from zero acres in 2013 to 90,000 acres of hemp production in 2018. Plantings were only reported in 4 states (Colorado, Indiana, Kentucky, and Vermont) in 2014, but then expanded to 22 states by 2018. Several states now have industrial hemp production programs, as well as medical marijuana programs; the difference between hemp and marijuana is the tetrahydrocannabinol (THC) amounts in plant tissue. Hemp is defined as *C. sativa* with 0.3% THC or less by weight. The novelty of this crop after legalization has led to a clear "lack of reliable, transparent data and peer-reviewed research and market information continues to be a challenge," and this has encouraged recent research in many aspects of growing *C. sativa* (Mark et al. 2020).

Cannabis sativa has a notably high terpene content similar to grape. *Cannabis sativa* produces cannabinoids (cannabidiol [CBD], THC, and others), VOCs, and phenolics. Hemp produces strong fibers that have many industrial purposes, but hemp's CBD content is desirable for neutraceutical products. Furthermore, *C. sativa* produces high amounts of VOCs which include terpenes. Monoterpenes and sesquiterpenes can be found in the plant's flowers, roots, and leaves (Andre et al. 2016). Dry weight in flowers contain between 3.1 to 28.3 mg/g of volatile terpenes with the main constituents D-limonene, β-myrcene, α- and β-pinene, terpinolene and linalool, β-caryophyllene, and α- humulene (Fischedick et al. 2010). Since other species of plants have been documented to emit VOCs (i.e., Eucalyptus, Lavander, *Arabidopsis,* and others) and there is evidence of terpenes taint/drift emitted by Eucalyptus, vineyard owners in California have begun to worry that *C. sativa* plants could cause a similar effect (Sellu et al. 2020). Sellu et al. (2020) studied the potential for *C. sativa* plants to drift terpenes on neighboring vineyards in experimentally designed plots. A 0.32-acre plot with two hemp cultivars (Boax and Cherry Wine Boax) were planted with the closest section only 68.5 feet away from established student research vineyards in Sonoma County, California. Cherry Wine Boax and Boax both have notably high terpene content relative to other cultivars of hemp. Terpene content of hemp plants were collected and analyzed by GC-MS for up to 5 weeks before harvest. Individual clusters closer to the hemp field were sampled at the same time frame. Grapes that were used to make wine were collected when the terpene content peaked in the neighboring hemp plants during the third week of data collection in early October. The terpenes in the highest concentration were myrcene, α-ocimene, and β-caryophyllene. There were no detectable terpenes found in the wines at this time. If wine grapes were tainted by hemp plants, there would have been an increase in terpenes that mirror the increase observed in hemp plants as suggested by Sellu et al. (2020). Additionally, Sellu et al. (2020) suggest that it is possible that any volatile terpenes could have been blocked by the eight-foot buffer rows consisting of corn and sunflower on either side, and the study would benefit from additional research in other wine regions, or with replication. Additional research is needed to determine if *C. sativa* has the potential to drift VOCs. Just as in Eucalyptus, terpene drift from hemp could prove to have desirable effect on the final product. Sensory panels would aid to this evaluation of desirable threshold

HEADING 6

CONCLUSION

Research done over the last decade provoked researchers and wine growers to question how plants surrounding vineyard sites can affect the aromatic profile in wines. This can be used to expand definitions of *terroir*. It is important to consider native plants and how they can influence aroma on wine aroma profile. Most research on this topic was done on *Eucalyptus* in Australia, but many other native plants have potential for the same effect. Whether these changes in aroma profile caused by terpene drift are considered negative or positive in final wine product should be taken into consideration as well. Other agricultural plants can influence aroma as well as discussed previously since some agricultural products produce strong aromas and emit high concentrations of terpenes. More research is needed to determine the ultimate effects of crops such as *Cannabis sativa* on wine aroma profiles since current studies only support the potential for this occurrence. In addition, it is important to note that other classes of compounds found in the environment can alter wine aroma. Smoke taints (Mirabelli-Montan et al. 2021), dairy farm decomposition aromas (anecdotal), Brown Marmorated Stink Bug (Mohekar et al. 2017) are just a few examples of sources for aroma taint that have been discussed. In addition to altering aroma profile of grape products, VOCs can alter plant functionality. Research on plant communication by VOCs can influence how plants respond to stressful stimuli such as salt stress, cold stress, insect threats, heat stress and others (Nincokiv et al. 2021). VOCs should be considered from a *terroir* point of view since they bring another dimension to where wine grapes are grown.

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