Terroir

An Integrated Wine Science Publication

BEE THE CHANGE

honey mead finds its niche

MODELING EXTREMES

predicting changes Down Under

A WRINKLE IN TIME

artificial aging

TUNE THE PRUNE

avoid canopy calamities

ICE WINE FRAGILITY

impacts of climate change

SOMETHING ROTTEN

moldy gold

SENSORY OVERLOAD

assessing the flavor of wine

MARKETING MAGIC

the able label

TAINT IT THE TRUTH

smoking is bad

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Terroir

An Integrated Wine Science Publication

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WINE SCIENCE

HOW CAN SOMETHING THAT TASTES SO GOOD BE SO INTERESTING SCIENTIFICALLY?

Working in small groups, students in ISCI 3A12 examine the science behind wine making, from the art of viticulture to its eventual consumption by the public. Students perform literature-based reviews and original research in order to understand the wine industry and its complexity; including the environmental requirements and consequences of winemaking, the short- and long-term health effects of drinking wine, and what factors contribute to the quality, aroma, and taste of wine. This research was formatted to resemble a publicly accessible scientific article, and compiled to create each Vintage of *Terroir*.

This Publication is written by members of the ISCI 3A12 class of 2020

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EDITOR: Russ Ellis

Get Buzzed:

Assessing the Past, Present and Future Economic Viability of Honey Mead

Zargham Ahmed, Khalil Husein, Michelle Kooleshova, Jennifer Ma, Maria Pricop

Mead may not be the first alcoholic beverage that comes to mind today, but it is indeed a strong contender for the first alcoholic beverage to ever be produced by human civilizations. It has held great cultural importance to several civilizations in our history; its production tied with the movements of the stars and key celebrations dating as far back as 10,000 BCE. This begs the question: how and why has mead fallen from popularity? Further, can the mead industry experience a resurgence? In this article, we seek to understand mead's past and future by exploring what difficulties in production mead makers face in the modern market and how these can be mitigated. This article also examines how the flavour profile and quality of mead change with respect to its unique honey terroir, identifies the challenges in and possible solutions to honey fermentation and aging, and recognizes how climate change may influence the sustainability of the mead market indefinitely. Keeping all this in mind, it questions whether mead has a future given rapidly changing climates, and the likelihood of a long-term revival of mead in the market. While the odds appear to be against mead, renewed worldwide popularity and novel research strive to keep this once-cherished beverage alive.

Historical Basis of Mead

Out of all the alcoholic beverages, none have quite the same historical and cultural significance as mead. Mead, otherwise known as honey-wine, was likely the first alcoholic beverage, made traditionally by diluting honey with water and letting the solution ferment with the addition of yeast[2].

To the modern mead aficionado, the beverage may conjure images of Old Norse Viking culture (4th – 6th century CE), but its history actually reaches as far back as 10,000 BCE[2]. Rock art from around this time shows ancient humans collecting honey from beehives[3]. Indeed, honey collection was one of the first organized agricultural practices, whereby early people would expel bees from their hives using smoke before collecting the honey. While it is unclear how exactly fermented beverages were discovered, it is likely that stored honey began to ferment with naturally-present yeasts. Once the product was consumed, the unexpected but pleasant effects of intoxication may have encouraged people to develop methods for deliberately reproducing the beverage[3]. The earliest evidence of intentional mead production comes from the detection of mead in pottery jars from around 7000 BCE, uncovered in Northern China, although evidence of mead exists in almost every ancient culture[2]. In fact, several regions around the world were likely independently producing mead at around the same time, since honey can be produced over a wide range of geographies[2].

With the introduction of mead, early evidence of beekeeping and the domestication of bees is also observed, starting from around 2500 BCE in Egypt[2]. As honey was the only sweetener available to most ancient cultures, beekeeping and mead production practices both spread quickly – so much so that honey and mead appeared across most, if not all, diverse cultures and languages of Western and Southern Eurasia[1]. The Egyptians likely first developed beehives made of clay or woven baskets covered with mud to expel bees out the back using smoke, perhaps an early practice of honey collection. Apiculture, or beekeeping knowledge, was then refined by the ancient Greeks, the Phoenicians, and finally, the Romans, who developed particularly advanced practices and at least nine types of beehives[2,3].

The importance of mead in the ancient world was also reflected in cultural traditions and mythology, as it was often seen as a gift of the gods. Mentions of mead frequent Norse mythology in tales about Valhalla, a majestic hall of celebration ruled by the god Odin. Drinking horns capped with metal were also customary for mead consumption specifically, as traces of honey compounds were later found inside using scientific analysis. These horns were often carried in a holster on the person, demonstrating the significance of mead in Norse culture (Figure 1)[1].

FIGURE 1: A Norse Drinking Horn, often used to consume mead[3,4]. These horns were capped with metal and carried around in a holster. Mead traditions were common in areas unsuitable for wine grapes, explaining the Vikings' notable enthusiasm for mead[2].

Similarly, gods of the Greco-Roman pantheon were said to consume ambrosia and nectar, both of which are honey-based and mead-like[5]. While the ancient Greeks and Romans are known as avid wine-drinkers, there was also a recognized time when mead took precedence in the Mediterranean. Mead was also popular during the Middle Ages, often brewed by early featured at the lavish dinners of King Charles II of England[5].

However, logistical challenges have always limited mead's longevity in the limelight, as the production time is lengthy relative to beer or wine and the price of honey is high[5]. As the onset of industrialization brought about a focus on productivity and mass production, mead eventually fell out of prominence in favour of beer in England. In Greece and Rome, the same practical limitations in mead production led to the rise – and eventual dominance – of wine[5]. As such, it is evident that in both Greco-Roman times and the Middle Ages, the alternatives were simply more cost and time efficient to produce, and mead's decline was exacerbated by changes in the natural environment that limited the supply of honey, making it a precious commodity[3,5]. The ebb and flow of mead's popularity throughout history is, therefore, a worn story that has been told many times, and continues to be told today (Figure 2).

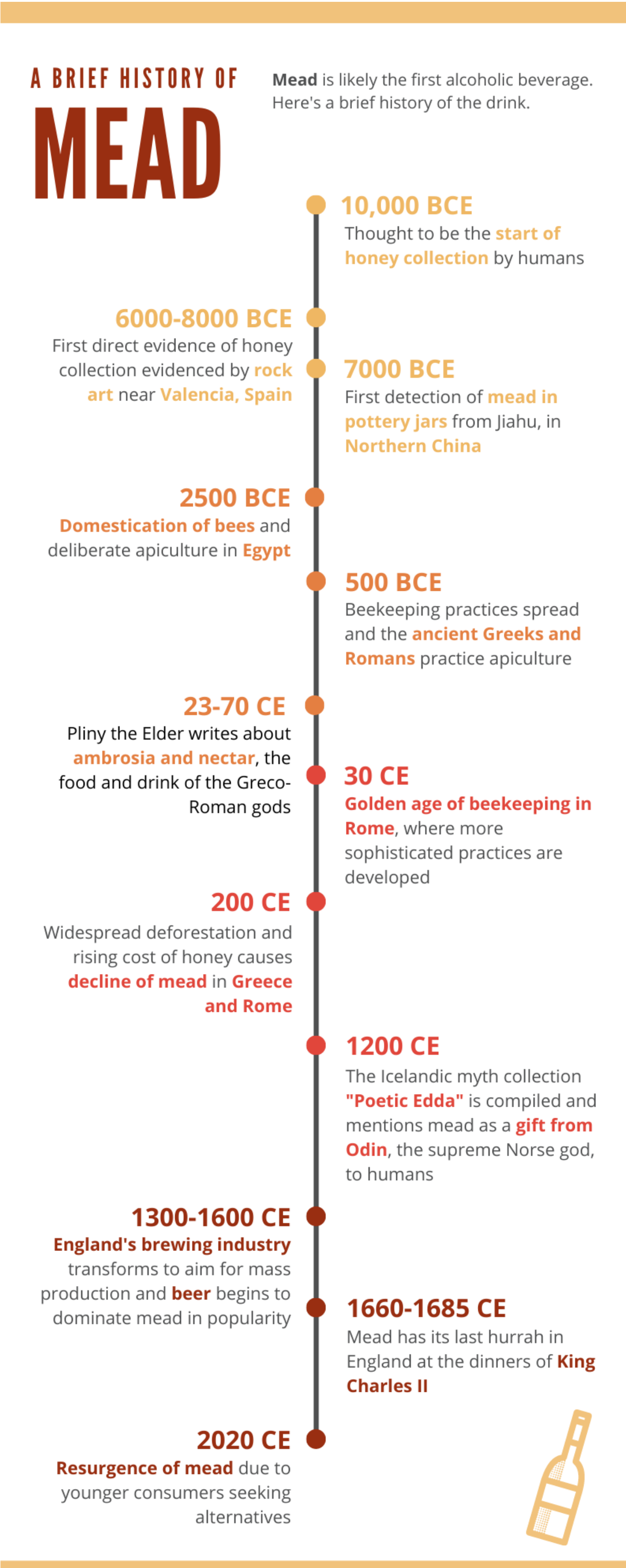

FIGURE 2: A Brief History of Mead, summarizing key events in its rise and fall in popularity throughout the centuries.

Today, the cultural changes stemming from industrialization, namely the focus on efficiency, have contributed to mead's place in the market as a niche product. However, it remains popular during the holiday season, particularly among craft beverage drinkers[6]. It now forms the smallest segment of the American alcoholic beverage industry, with meaderies accounting for 2% of all wineries in the US[7]. However, the industry has experienced growth over the past few years, partly due to contemporary branding targeting younger consumers[7]. It is clear that mead, once heralded as the "beverage of the gods," no longer enjoys the same cultural prestige and relevance that it once did. This article explores the role that various aspects of mead production, including honey terroir and fermentation, may have played in the decline of its popularity throughout the years, as well as the potential future of the industry in the wake of climate change.

Mead in the Current Market: Variability and Viability

To analyze the future of the mead industry, it is important to begin by looking at the various factors that contribute to the current economic viability of mead in the market. The variability of the final mead product is a major factor, as the characteristics of mead are impacted by the surrounding environment, or terroir, of the honey used to produce it, as well as by the fermentation and aging processes described later. Specifically, the flora that bees pollinate when producing honey defines the qualities mead retains after subsequent processing[8]. The terroir of the honey thereby introduces a significant source of variability in the production of mead, as environmental conditions may shift over time and geographic location, translating into economic uncertainty for mead producers[8].

Many studies have investigated how different floral sources impact the flavour of mead, and which of these sources tend to produce meads with a more appealing taste and overall higher quality[8, 9, 11]. In addition, honey from different floral sources impacts the fermentation process, resulting in variation in the relative amounts of flavour-producing compounds and volatiles in the final product[8]. Some primary factors highlighted herein that are responsible for mead's flavour profile include: the level of volatile acids, esters, residual sugars, and alcohol content[8].

For example, alcohol content is found to be much higher in mead produced from multifloral honeys. Specific alcoholic compounds can contribute to different classes of flavour and odour[8]. Of these compounds, a larger amount of the alcohol α-phenylethyl, primarily found in multifloral honeys, is likely to impart more "rosy" and "honey-like" odours and flavours[8].

Volatile esters make a significant contribution to the flavour profile of mead as well. These compounds are most prevalent in acacia meads produced using honey derived from any plant or tree in the *Pseudoacacia* species, which are native to North America and parts of Europe[9]. Additionally, honey derived from *Vitex* plants native to the Mediterranean, such as Chasteberry trees[10], have the largest variety of esters[8]. The most abundant esters in these types of mead are ethyl octanoate, ethyl dodecanoate, and ethyl 9-decenoate, which contribute to more desirable "fruity" or "floral" odours and flavours[8].

Volatile acids such as octanoic acid, acetic acid, decanoic acid, and hexanoic acid are also most abundant in meads produced using acacia honey[8]. These compounds tend to result in meads that have more "fatty" or "cheesy" flavours, contributing an undesirable "rancid" odour to the final product[8].

The combination of these factors speaks to the breadth of odours and flavours that mead can acquire. Simply changing the type of honey used in production can significantly impact the flavour and aroma profile of the final product[8]. Assessing the degree to which different types of honey can affect mead's qualities is interesting. It is, however, important to understand that this variability can cause many issues for the economic viability and marketability of the beverage. This issue of marketability becomes more apparent when comparing the sensory characteristics of meads produced with different types of honey.

Professional mead tasters are employed in studies to provide insight on the sensory characteristics of mead, such as flavour and aroma. Meads produced from multifloral honeys, as well as honeys derived from jujube plants, a plant native to South Asia and parts of China[11], have been rated as having the best aroma quality, highest aroma intensity, and the highest taste quality[8]. On the contrary, meads produced with acacia honeys and vitex honeys are the lowest rated in these categories[8]. This is likely a result of the variations in the chemical compounds present, as noted earlier, as acacia honeys were high in volatile acids that can contribute to negative flavour and aroma profiles[8].

These observations make it apparent that variability in the flavour profile, that stem from the floral source of honey, can impact the marketability of mead. The flavour profile can therefore be significantly altered in both positive and negative ways, which influcences how the public perceives the product and thus, how well it sells. This is especially important when looking at the economics of mead production in addition to the challenges that will be faced due to climate change. Different plants have unique climatic requirements, and alterations will result in significant changes to the honeys available in specific regions. These inconsistencies can further impact the marketability of the mead.

Mead Fermentation and Aging

Fermentation and aging pose additional challenges contributing to the decline of the mead industry.The fermentation and aging of mead are complex, multi-step processes controlled by a variety of factors that introduce both exciting potential for optimization, as well as uncertainty in mead production[12]. Mead producers therefore have the opportunity to make a high-quality product, at the risk of being unable to recreate it year after year. When sugar and water are available in the environment, yeasts metabolize these ingredients to produce energy and survive[13]. The byproducts of this metabolism—namely, ethanol and carbon dioxide—are used in the production of alcoholic beverages (Figure 3)[13].

$$C_6H_{12}O_6 \rightarrow 2CO_2 + 2C_2H_6O + 2ATP$$

Glucose → carbon dioxide + ethanol + 2ATP

FIGURE 3: In Alcoholic Fermentation, yeasts use glucose (sugar) as an energy source, metabolizing it to carbon dioxide, which provides carbonation, and ethanol, which lends mead its alcohol content. The more glucose that is available to fermentative yeasts, the higher the predicted alcoholic content of honey mead.

Honey's high sugar content makes it an optimal candidate for fermentation, and the characteristics of the final mead can be attributed to the nutrients that are available to yeasts via terroir, as well as the fermentation rate of the honey. Honey consists of an approximately 20% or lower moisture content and 75-80% sugar content[14]. Yeast preferentially metabolizes glucose, and any sugar that is not converted to ethanol within this process is known as residual sugar[14]. High residual sugar content lends mead its desireable sweetness and balances the acidity of ethanol produced by yeast, decreasing the astringency — or pickle-like taste — of the mead, thereby improving its flavour profile.

Following the fermentation process, mead must be aged and bottled before selling. During the aging process, suspended particles, including dead or live yeasts and pollen, precipitate from solution, increasing the clarity of the mead[15]. Aging is also important in the development of aroma compounds, and in reducing the volatility of the mead, thereby increasing its sensory profile[15].

Bioindicator: An organism capable of reflecting the health of their ecosystem.

Several problems can arise throughout fermentation and aging and the longer each process lasts, the more likely it is that complications will occur[16]. In fact, this is part of the reason for mead's notorious inconsistency and the hardship mead producers face when trying to recreate their product year after year[16]. Currently, *Saccharomyces cerevisiae*, a species of yeast used in wine production, is also the most commonly used in mead production[13]. A problem arises though, since the components of honey differ from those of grapes, leading to different levels of stressors placed on yeasts during fermentation[13]. Fermentation may also stop prematurely, resulting in a too-sweet mead with little alcohol[15]. Conversely, yeast can begin to re-ferment sugars in the mead. When this happens, the timeline for fermentation is shifted and too much ethanol is produced too early, resulting in a sour, unpleasant taste and a noxious aroma in the mead[15]. High levels of ethanol and low levels of available nutrients can decrease yeast populations drastically, slowing down fermentation and productivity. Long fermentation and aging times also make mead prone to bacterial colonization or infiltration by fruit flies, both of which can spoil entire batches of mead within a day[13,15]. Bacteria may introduce acidic byproducts that interfere with the process at hand, or foul the taste of the mead[15,17].

Yeasts also require sufficient concentrations of Yeast Assimilable Nitrogen (YAN), which optimizes fermentation kinetics[18]. While honey tends to contain low levels of YAN and other such nutrients, pollen has a high concentration of nitrogen and has been shown to act as a fermentative activator, which can make pollen addition a solution to problems with fermentation due to yeast stressors[18]. Pollen addition can improve fermentation kinetics, increasing alcohol yield and enhancing the flavour profile and mouthfeel of the final product[18]. The pollen contributes its own unique characteristics to the mead, depending on its source, the physiological health of the pollinating bees, and the minerals the pollen contains[18].

Researchers from Spain and the Netherlands explored the impact of varying pollen concentrations on the fermentation kinetics, physical, and sensory characteristics of mead[14]. They found that the fermentation time for honey without pollen was 43 days, and that pollen addition decreased this period to eight days[14]. This difference can translate into increased economic efficiency by speeding up the production rate and decreasing the time it takes for the product to get to market. Notably, the addition of insufficient quantities of pollen resulted in mead that was too sweet, while excessive pollen resulted in an acidic mead that was too sour[14]. The researchers concluded that a moderate pollen concentration of 30 g/L was the ideal compromise between proper fermentation and an optimal sensory profile, especially when it came to balancing cost in the context of large-scale production[14]. Other fermentative activators can also be used to optimize the fermentation process, all of which are nutrient-rich solutions for yeasts, ensuring they have all of the nutrients necessary for successful fermentation[12].

Fermentation and aging can, therefore, be complicated by a number of factors including a lack of honey-optimized yeast strains, as well as by ethanol stress, re-fermentation or spoilage. Pollen addition during fermentation can help mitigate the risks of re-fermentation or fermentative arrest by ensuring yeasts have sufficient nitrogen to effectively metabolize glucose. Aging can also be safe guarded via proper sanitation and bottling practices that prevent bacterial colonization and insect invasion[15]. Without more research conducted in understanding the scientific details involved in fermentation and aging, the mead industry may miss out on a plethora of opportunities for growth. Scientific investigation is thus paramount to improving the efficiency and consistency of mead production given all of the variability introduced by honey terroir, mead fermentation, and aging.

Climate Change

Beyond the challenge of producing a desirable mead, with respect to choice in honey, and the rather recalcitrent process of its fermentation, exists another possible hurdle in the mead industry's future. That is climate change. Vintners, oenologists, and wine connoisseurs alike are well aware of climate change and what changes may arise in vineyard locations and the availability of wine delicacies—issues that mead producers also experience. Namely, the mead industry may have to accommodate changes in honey bee habitat ranges and the availability of pollen sources, as species adapt to newer climates, Similarly, the general public has been made aware that honey bee populations have been declining. Honey bees are sensitive to change in their environment, and are often regarded as bioindicators due to their vulnerability. Climate change may have very real consequences for honeybees and ergo, mead makers. In apiculture, when there are local extinctions of bee populations, the usual suspects are disease, pesticides, and pollution; but what happens if bee extinctions become a global phenomenon?

The ecological services of honey bees, namely pollination, and its significance motivated researchers to look for changes in worldwide bee populations[19]. They compiled a database containing upwards of 400 000 georeferenced data points corresponding to 67 honey bee species from North America and Europe to analyse the movement of honey bee populations[19]. It is expected, on average, disregarding external and anthropogenic-driven causes such as habitat loss through deforestation, that as the global climate warms, a species' habitat range will shift and expand northwards[19]. However, this has not been the case for honey bees. While their southern habitat range has decreased over time, there are no observed northward expansions[19]. Thus, the habitat range of the honey bees is becoming increasingly limited. Climate change is the primary suspect for this, as neither changes in land or pesticide use were found to be significantly associated with this trend[19].

Bees are heterothermic, meaning that their bodily temperature can be a product of either the environment or their own body's regulation[20]. This rather unique trait should, in theory, give honeybees an advantage, but it is more complicated than that. It is difficult to predict how bees, including honeybees, will adapt to the projected change in climate. To investigate this, researchers from Spain monitored the hives of native Spanish honeybees, *Apis mellifera iberiensis*, throughout the flowering seasons, 2016 through 2017, during which drought and high temperatures occurred[21]. Remote observations of the adult bee population, bee brood, and pollen and honey reserves were recorded at regular intervals[21]. Drought contributed significantly to the shortening of bloom periods and therefore, relative scarcity of pollen. Pollen is a necessary source of food and protein for bee colonies[21]. The scarcity was a cause of food stress for the Spanish honey bees, and colonies experienced a decline in number of adult bees and average body weight[21]. Changes in blooming periods also contributed to changes in the available pollen. The ratio of pollen sources became skewed in favour of blooms with a stronger affinity for the drier, warmer climate. This, therefore, affected the characteristics of the commercial honey extracted. This poses a challenge for mead makers, as it increases the difficulty of finding honey which will yield a consistently favourable mead flavour profile.

Changing climatic conditions are a source of concern for mead producers on multiple fronts. As honey bee habitat ranges become constricted and the variation in pollen sources fluctuates, mead makers may experience more difficulty finding sources of suitable honey. This leads many to question whether the business of mead will remain sustainable, as the honey it requires becomes more scarce and more labour intensive than ever before.

The Future of Mead Production

Since the advent of agriculture until the relatively recent rise of industrialization, which is characterized by a preference for efficiency, mead's popularity as an alcoholic beverage was indisputable and has played an important role in the culture of ancient civilizations[2]. Thus far, we have discussed how challenges and uncertainty in the production of mead, particularly in its terroir as well as the fermentation and aging process, have contributed to the observed sharp decline in the consumption and economic viability of mead[22]. These difficulties are only heightened by climate change and the resulting decline in bee populations. Within this rather gloomy portrait of mead, is there a future for it at all?

Curiously, there has recently been a global resurgence in mead's popularity. In the USA, for example, the number of meaderies has climbed to nearly 500 in 2020, from 30 in 2003[23]. This renewed popularity is thought to be due to younger consumers searching for alternatives to standard alcoholic drinks. While still occupying a small niche in the alcoholic beverage market, the past two decades have seen increased experimental work to make mead a more economically viable beverage[24].

Recent research has focused on the study of methods and techniques to increase the effectiveness and efficiency of mead production[24]. Researchers at a University in Brazil determined that sufficient nitrogen should be supplemented during fermentation to obtain a concentration of 150 mg/L of yeast assimilable nitrogen[25]. While nitrogen is the most important nutrient, to optimize fermentation efficiency, potassium ions should also be supplemented in tandem to obtain a potassium concentration of 465 mg/L. In addition, small quantities of a variety of minerals and vitamins are required to initiate successful fermentation[25]. As mentioned earlier, pollen has a nutrient profile similar to this description[14]. Pollen has shown promise in enhancing the mead production process and may be utilized to produce higher-quality mead in a shorter amount of time. Scientists from a university in Portugal developed their own custom nutrient supplement based on a review of the literature. They found that it supported the fermentation process more effectively than commercial supplements, suggesting there is room for optimization of current supplements[13]. They also found that fermentation had a greater probability of successful completion using dark honeys compared to light honeys. To reduce the prolonged aging timeline for mead, artificial aging mechanisms used in wine production have been proposed for use in mead production[26].

The widespread decrease in honey availability has become a growing topic in mead research and multiple unique solutions have been proposed. In one example, the honey industry has recently faced a drastic increase in the prevalence of 'fake honey', which is primarily derived from corn syrup containing added honey elements[27]. The cost to produce this alternative honey is significantly lower than real honey because of its ingredients, provoking the question of its use in mead production. However, the majority of research on this concludes that the impact of 'fake honey' on the economic market is primarily negative, and could harm the honey industry indefinitely[28]. In the case of mead, consumers particularly value authenticity in their beverages and using 'fake honey' would flout expectations, driving away customers[29].

Did You Know? Mead has many therapeutic properties which complement the growing trend of healthy alcoholic beverages[30]. Namely, mead has relatively high antioxidant activity, and can provide a boost to the immune system. Additionally, it can provide probiotic benefits to the gastrointestinal system[30]. Long-term mead consumption may even decrease the risk of developing cancer!

Recent research has suggested the use of alternate practices to mitigate the effects of climate change[31]. Renewed focus on sustainable beekeeping, reducing dependency on pesticides, and honeybee habitat restoration is important for the creation of a resilient, productive agrosystem.

Even if the production of mead is streamlined and made more efficient, mead still needs to find its place in the market such that it is not overshadowed by wine[32]. Depending on the honey used, as well as the use of additives, a diverse array of beverages can be created which fall under the umbrella term of mead, such as melomel (Figure 4). As aforementioned, the floral source of honey plays a crucial role in the sensory profile of the resulting mead, and sources used to produce mead preferred by consumers should be prioritized in future mead production[8]. As multiple different additives and sources can be used, mead is highly customizable and can cater to a wide variety of consumer preferences. This flexibility in customization may allow mead to be desirable to a diverse global audience and stand alongside wine in the market[32].

FIGURE 4: A Container of Melomel, a variant of mead containing fruit as an additive[33]. Variants such as melomel allow mead to cater to a larger and more diverse audience.

The future of mead is fraught with uncertainty and current obstacles in its production certainly stack the cards against it. Despite this, its worldwide revival in popularity stands in defiance against its otherwise bleak forecast and has motivated research efforts that work to establish a more permanent place for mead in the alcoholic market. It is contentious whether this renewed activity in the field is capable of establishing a more stable and long-term future. However, it is guaranteed that collaborative initiatives between scientists and mead producers will play a pivotal role in potentially elevating mead back to the revered status it relished in thousands of years ago.

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Cheating Time:

How Artificial Aging Reinvents the Barrel

Cohen Bolliger, Hunter Clark, Guillaume Hewitt, Brandon Nicholson, Will Roderick

As early as ancient Greek and Roman times, wine has been stored and aged to improve its quality. Ever since, aging has allowed for the steady and controlled development of flavourful and aromatic compounds within wine, as well as the contribution of oaky flavours by wooden barrels. With the advent of sophisticated 'artificial' wine aging systems like microoxygenation and the use of alternative oak products, we may see a reduction in the cost and time required to age wine. Furthermore, these gains do not sacrifice quality in wine taste or experience. This results in a flavourful wine at a fraction of the cost. This article provides a comprehensive review of the techniques and chemistry of traditional and artificial aging.

INTRODUCTION

When purchasing a bottle of wine, red or white, you may have noticed on the label that the wine has been 'aged' or 'matured'. While this declaration may lack meaning to most, aging or storing wine changes its aroma, colour, and mouthfeel. This is because, like many other consumable goods, wine is perishable and contains chemical compounds that change over time. Unlike many other consumable goods, wine is aged in very controlled conditions with the expectation that its flavours and characteristics will develop to make the wine more enjoyable to drink.

However, the process of aging wine comes with costs and risks. Not only do wine producers have to withhold the product from the shelves, resulting in delayed profits, but they must also consider the costs of storing the wine in expensive wood barrels. To mitigate this, wine producers can depart from the lengthy and expensive barrel aging process and adopt alternative methods. This is referred to as 'artificial aging'. Methods like micro-oxygenation and the use of alternative oak products have the potential to shorten the process of aging without sacrificing the quality produced by traditional barrel aging.

AGING PROCESSES

While many wines may be enjoyed right after their fermentation or even after a few months of aging, one of the most popular styles, dry red wines, requires years of aging to reach peak condition. The reason for this has to do with the development of their internal chemical structure. Red wines are fermented in the presence of their grapes' skin and seeds, while white wines are not. Consequently, phenolic compounds leach into the juice. These phenolics give red wine its unique and desirable characteristics, notably tannins, which confer astringency, and anthocyanins, which confer different colours [1,2].

Anthocyanins come only from grape skins and have various chemical configurations corresponding to different colours. Certain pairs of hues reside in equilibrium with each other, and the addition of specific chemicals or conditions can cause an imbalance[1], as can be seen in **Figure 1**. A major consequence of adding sulfites, usually for antimicrobial purposes, is a shift of red anthocyanins to their colourless form, a process dubbed sulfite bleaching[2]. In the presence of minor oxidation, anthocyanins form pyranoanthocyanins, which give off an

Chemistry not your thing? Here's a list of useful terms.

Anthocyanin: Organic phenolic pigment molecule that gives certain foods red, purple, and yellow colours.
Astringent: a dry, bitter feeling in the mouth caused by the contraction of cells.
Hydrolysable: a type of tannin that can be broken down when exposed to heat, acids, or bases.
Phenol: Organic molecule that is aromatic (in a ring), with a hydroxy group (-OH).
Tannin: Organic polyphenolic molecule that binds to saliva proteins, giving an astringent effect.

orange-red hue and are more resilient to colour-changing, bleaching and hydration reactions[3]. However, oxidation also increases the rate of polymerization, and if the compounds become too large, they will precipitate out, contributing instead to a yellow-brown hue[2].

Flavanols are the natural tannins that come from the grape skins and seeds which contribute to the bitterness and mouthfeel, or astringency, of the wine[4]. The size of the flavanol molecules influences the degree to which these qualities are experienced. Small and monomeric flavanols are more bitter, whereas larger flavanols pull more proteins out of your saliva, causing a stronger feeling of astringency[5]. However, just like anthocyanins, if they get too large, they precipitate and decrease astringency.

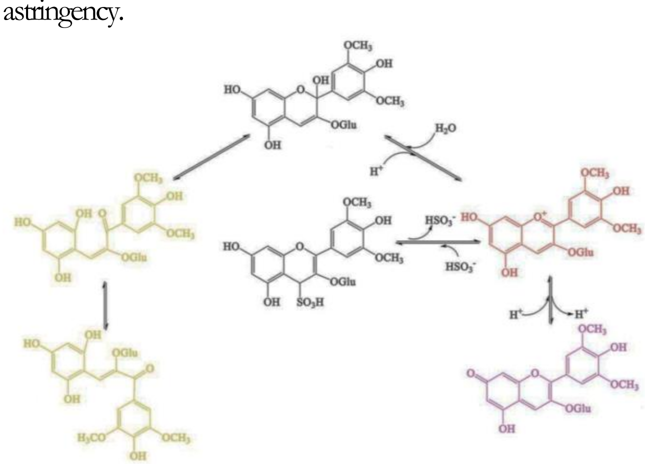

FIGURE 1: ANTHOCYANIN PIGMENTS. The chemical reaction pathways for the various anthocyanin configurations, and their respective colours. Adapted from Li & Duan[2].

Anthocyanins and flavanols have an interesting relationship that allows them to interact with each other in a process called indirect polymerization. Two anthocyanins can bond to the ends of a flavanol chain, causing both to be stabilised[2]. This stops them from precipitating, stabilizing the colour and astringency[3]. The ratios between anthocyanins and flavonols are also important for colour and phenolic development. One study examining the effect of oxidation on different ratios of anthocyanin to tannin extracts showed that higher levels of seed tannins increase polymerization in the presence of oxygen[1]. Notably, oxygen seemed to increase tannin polymerization more so than anthocyanin polymerization, creating more anthocyanin monomers.

OAK BARRELS

Oak barrels have been used for hundreds of years as an ideal environment to facilitate aging reactions. Oak is used because of its relative impermeability to liquids and its high levels of phenolic compounds, which are extracted by the wine[5]. The most important compound is a hydrolysable tannin called ellagitannin[3]. These can react with flavanols to create flavanol-ellagitannins, which are much less likely to impart astringency on the wine and leads to the wine becoming less harsh, or "softening", with time[5]. Ellagitannins have better antioxidant properties than flavanols, which helps to protect the other phenolic compounds from oxidation[2]. Both tannin compounds facilitate the indirect polymerization of flavanols and anthocyanins[3]. The other major contribution of the barrels is the wood's porosity, which allows for limited amounts of oxygen to seep in over time, causing gradual change without overoxidation occuring[2].

There are two major ways of treating the wood to change its chemical composition. The first is seasoning, where open air and small amounts of heat help to decrease the wood's moisture content[5]. This causes the degradation of its macromolecule tannins into their smaller phenolic compounds and increases the rate of oxygen transfer[2]. The other method is toasting, shown in **Figure 2**, where heating the wood to very high temperatures in short intervals achieves an almost complete degradation of its tannins[5]. Although this takes away from typical barrel aging processes discussed earlier, it allows for a greater amount of phenols, whose intricate interactions increase the complexity and depth of the wine. As all wines are different and chemically complex, the extent of aging and the conditions surrounding it are not standard. This means that there are many factors that can be manipulated to produce a perfectly aged product.

FIGURE 2: OAK BARREL TOASTING. A barrel being treated in the form of toasting. The level of heat and charring will break down the ellagitannins to alternative forms, which will contribute to diverse flavour profiles[6].

THE ROLE OF OXYGEN

A critical element to the successful aging of any wine is correct oxygen exposure. Oxygen is important for oxidation reactions, which notably produce acetaldehyde (nutty, sherry-like aroma) and acetic acid (vinegar aroma)[7]. Furthermore, oxygen stabilizes wine colour and reduces astringency through polymerization. As with any other food, excessive oxidation can be detrimental to the organoleptic qualities of the wine. The overexpression of acetaldehyde produces "flat" flavours and the overexpression of acetic acid makes wines too vinegary[7]. Overoxidation can also cause off-colours and precipitates to form. Conversely, wines aged without oxygen may see overexpression of reductive compounds, which can give a musky or "foxy" flavour to the wine[8]. As such, care must be taken to ensure that wines not only receive a correctly calibrated amount of oxygen, but also that the oxygen is added slowly to prevent excessive oxidative reactions. Since oxygen mostly degrades phenolic compounds primarily found in grape skins and seeds, which are not used in white wine making, oxidation is usually only beneficial to the flavour of red wines[9].

The role of oxygen in wine is intrinsically tied to the catalytic effect of metal ions in the wine solution, the most important of which is the ferrous ion (Fe^{2+})[9]. In its most common triplet form ($^3O_2$), oxygen has two unpaired electrons or radicals but is not very reactive to organic substances due to the antibonding properties of its radicals[8]. Instead, triplet oxygen is reduced into reactive oxygen species through catalytic metal ions, as shown in **Figure 3**[9]. This leads to the formation of hydroperoxyl radicals ($HO_2\cdot$). Though this form is not reactive enough to take hydrogens from many substrates and thus become stable, phenolics are sufficiently hydrogen-donating to allow this reaction if they form a stable product radical[9]. Hydroperoxyl radicals can be further reduced to form the much more reactive hydroxyl radical ($HO\cdot$), which is much less selective about the compounds it reacts with, reacting with all compounds in proportion to their concentration. This species is important for the oxidation of alcohols, especially in the formation of acetaldehyde from ethanol[9]. The oxidation of wine can be controlled by antioxidants, which reduce the reactive oxygen species and quinones (oxidized phenols). In wine the most common antioxidant is sulphur dioxide, which is naturally introduced by yeast metabolism[9].

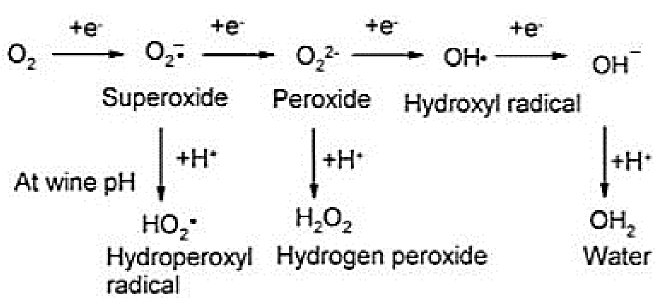

FIGURE 3: OXYGEN REACTION LADDER. A schematic showing the oxidation of triplet oxygen into reactive oxygen species, with each step catalyzed by a transition metal ion. Adapted from Waterhouse and Laurie[9].

While oxygen is added in significant amounts during the winemaking processes such as in pressing and bottling, an especially critical element of oxygen addition is barrel permeation[9]. Notably, traditional barrel aging allows for the slow and relatively constant addition of oxygen into the wine, which reduces the effect of differing reaction rates[10]. However, quantification of the exact amount of oxygen which enters through the barrel is complicated by many factors. For example, new barrels are roughly three times more permeable than used barrels[11,12]. Another complicating factor is the species and origin of wood used, as they confer different densities and porosities to the barrel[10,11]. Furthermore, when the barrel becomes wet, as happens when wine soaks into the wood, oxygen permeation is greatly reduced[12]. Therefore, while oxygen transfer into the wine is a critical aspect of aging, it can be extremely hard to make informed decisions about its management in traditional aging systems.

ALTERNATIVE OAK PRODUCTS

When considering the artificial aging of wines, there are many techniques that have been explored or suggested, but the only one that has gained much popularity and a modicum of public acceptance is the use of alternative oak products (AOPs). An alternative to traditional barrel aging, AOP use involves adding oak in the form of chips, shavings, or staves to wine aged in stainless steel containers. This has been explored since the late 1900s and is even being used in some commercially available wines[11].

The first factor that affects the flavour and aromatic compounds imparted to the wine is the shape and size of the AOPs. There are several compounds that are extracted from the oak over time that impart specific flavour notes to a mature wine, such as furfural (dried fruit aroma), guaiacol (burn overtones), oak lactone (coconut, woody aromas), eugenol (spice aroma), vanillin (vanilla character), and syringaldehyde (vanilla character). Different sizes of wood chips will contribute different compounds at different rates, both when compared to each other and to traditional barrel aging. Wines aged with chips extract a similar amount of furfural, vanillin, and syringaldehyde, regardless of size, while those aged with larger chips extract much more guaiacol in the same period of time[13]. When compared with classically barrel-aged wines, the chips extract similar quantities of organoleptic and aromatic compounds in 7-14 days as opposed to three months in a barrel. This increase in compound extraction is most often accredited to the increased surface area of wood in contact with the wine at any given time. Additionally, in experiments studying the differences between staves and chips, it was found that staves produced more furfural and its derivatives, while chips were associated with more vanillin. Interestingly, chips were also associated in some cases with the production of compounds related to off-flavours in wine, such as 1-hexanol and 1-hexanal, which confer green plant flavours[14].

Another factor that affects wine flavour is toasting. Much like in traditional barrel aging, AOPs can be toasted to varying degrees. Toasting level contributes several characteristics to the wine, including flavour, mouthfeel, and colour. **Figure 4** illustrates some of the differences between toasting levels.

When AOPs are used, the level of toasting imparts flavours similar to those of a barrel toasted to the same degree, but in a much shorter time period[15]. Medium toasted chips and staves are generally associated with an increase in brown colour, as well as spicy, vegetative, woody, and smoky aromas and flavours. Heavy toasting is also associated with these aspects, but to a lesser extent, and has increased nuttiness and earthiness. Lightly toasted chips are associated with coconut flavours. When compared to wines aged in a wine barrel, those aged with AOPs in a stainless steel container for the same amount of time have dramatically increased and more pleasant flavour[15].

FIGURE 4: THE EFFECTS OF TOASTING. A visual representation of the varying levels of toasting that can be applied to wood being used to age wine, both via AOPs and traditional barrels. The primary flavour associated with the level of charring is indicated as well[16].

MICROOXYGENATION

Studies have shown that while aging wines with AOPs alone improves organoleptic qualities, the results become more pronounced when AOPs are paired with microoxygenation (MOX). MOX is a technique that was first put into practice by Patrick Ducournau in the 1990s[17] and involves a large steel container usually 2.2 meters in height that is connected to oxygen cylinder[18]. A common setup, shown in **Figure 5**, is to pump oxygen from the cylinder into the wine in the container through a porous ceramic stone that is located at the bottom, a process known as bubbling[19]. The height of the steel barrel is significantly taller than the standard oak barrel to ensure that oxygen bubbles dissolve into the wine rather than collect at the top[18]. MOX primarily uses a bubbling method to ensure that the oxygen disperses throughout the wine while maintaining a slow continuous flow rate, comparable to that of a barrel[18]. This is a delicate process as winemakers have to ensure the rate of oxygen introduction is less than or equal to the rate of oxygen consumption by the wine[18]. If too much oxygen is added then it accumulates in the headspace, resulting in excessive oxidation[19]. This can lead to a multitude of negative effects, such as browning, precipitate formation, phenol oxidation, perception of tannin dryness, higher astringency, loss of wine freshness, oxidized aroma, and adverse microbial activity[19].

DID YOU KNOW? Due to the military atomic tests conducted from 1950 to 1963, grapes grown and collected for wines during this period and afterward contain trace levels of cesium 137. We can verify that a wine is dated after 1950 if we detect photons released from cesium 137 decay[22]!

To minimize the chance of excessive oxidation, wineries using MOX closely monitor parameters such as temperature, free sulphur dioxide levels, and wine pH, as they affect the amount of oxygen consumed[19]. MOX works best between the temperatures of 14 and 17 °C, with higher temperatures resulting in poor oxygen solubility and lower temperatures resulting in the accumulation of oxygen in the headspace due to slower reaction rates. Free sulphur dioxide levels are important in regulating how much oxygen is consumed by the wine and so fluctuations must be monitored to allow for oxygen flow adjustments. The rate in which the wine consumes oxygen is also heavily dependent on wine pH: the higher the pH, the more oxidation will occur[19]. The main objective of using MOX and AOP in unison is threefold: it lets wineries save money as they do not need to invest in barrels and can reuse containment systems, it is easier to control the levels of oxygen within the system, and it saves a significant amount of time as the process is much shorter[19].

DID YOU KNOW? In Ancient Rome, most citizens put a higher value on aged wine even if the quality was inferior. As a result, the Roman populace made use of buildings known as fumarium which were used to artificially "age" wine by imparting a smoke flavour into the wine itself. The wine was "aged" in an amphora (a clay jar). The smoke's interaction with the wine imparts a paler colour and sharpens the acidity[23].

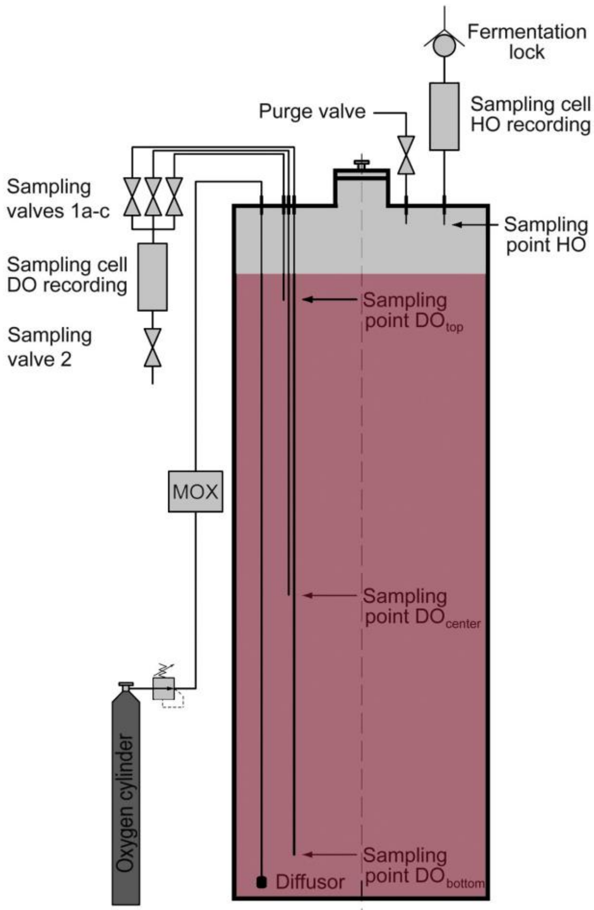

FIGURE 5: STANDARD MOX SETUP. A visual representation of the MOX system that is commonly used within wineries., where HO is headspace oxygen, and DO is dissolved oxygen. Adapted from Durner et al.[20].

MARKETABILITY CONCERNS

Despite the obvious cost and time saving benefits of MOX and AOP techniques, their use is not widespread throughout the industry. The reality is that many wine traditionalists object to the practice, as exemplified by a French ban on the use of wood chips[21]. This leads consumers to view a traditionally aged bottle of wine as superior to an artificially aged bottle of the same variety. The other downside to artificial aging is that it does not perfectly replicate a traditionally aged wine, as the same chemical reactions occur but to different extents in a significantly shorter amount of time. Even though MOX and AOP aging gives a similar tasting product to traditionally aged wines, it must be acknowledged that on a fundamental level, the resulting wines are different. While the differences would be mostly undetectable to the average wine consumer, a connoisseur may be able to detect them.

CONCLUSION

Micro-oxygenation and alternative oak products have the potential to reinvent the way wines are aged by reducing the cost and duration of the aging process. Traditionally, oak barrels allow the slow diffusion of oxygen and oak flavours into the wine and provide a stable environment for chemical reactions. Using a micro-oxygenation device to imitate the permeability of a barrel increases the precision in delivering oxygen to the wine. Alternative oak products like chips and staves eliminate the need for an expensive barrel while increasing the surface area of wood exposed to wine. By combining these techniques, wine producers can avoid the lengthy and expensive traditional barrel aging process. For these novel techniques to be implemented on a broader scale, viticulturalists will need to overcome the negative connotations associated with an 'artificial' process.

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Icewine & Climate Change:

How will climate change impact the largest Icewine producers in the world?

Sydney Deslippe, Margot Ferguson, Stephanie Koza, Selvi Patel, and Evlyn Sun

This article investigates the impact of climate change on Icewine production in the Niagara Region. Canada is a leading producer of Icewine with the Niagara Region being one of the only suitable areas to support Icewine production. As a result, Icewine has become a delicacy in Canada. That being said, the industry faces a large threat from temperatures rising due to climate change. The impacts of climate change to date are minimal and have not drastically affected the Icewine industry. However, this may change in the future. Temperature projections are analyzed here to examine potential future climate trends and understand how long-term implications of climate change may affect Icewine production. Many potential adaptation methods are also identified, which can be implemented to combat this issue. This article demonstrates the possible threats of climate change and the need for precautionary action to sustain the Icewine industry.

INTRODUCTION

This article focuses on a type of sweet wine called Icewine. In general, sweet wines refer to wines that contain elevated levels of residual sugars (sugars that are left over after fermentation by yeasts)[1]. Icewines are made from grapes naturally frozen on the vine and harvested in the winter. Icewines likely originated by chance as a result of unfavourable growing seasons. The first Icewine harvest was fully documented in 1830 when wine growers left grapes on the vine to freeze, under the assumption that they could be used as animal fodder. When the frozen grapes were pressed, however, they discovered that the must was of high quality and extreme sweetness[2].

The dominant producers of Icewine are Germany, Austria, and Canada, with China having the biggest consumer market[3]. Icewines are expensive to make, with 3-4 kg of grapes required to produce a 375 mL bottle. This is equivalent to approximately one glass of Icewine per vine or about one drop of Icewine per grape[2]. Icewine is also difficult to make because of the conditions required for its production; cold and often extreme climates are ideal for production, but these climates make soil conditioning and vineyard management very difficult. There are also requirements governing Icewine production depending on where the grapes are grown. In Ontario, the Vintners Quality Alliance (VQA) sets guidelines for how grapes destined for Icewine can be grown. Icewines must meet these guidelines and be approved by the VQA in order to be produced in Ontario. Sugar addition is prohibited, for instance, as is artificial freezing, and Icewine grapes must be harvested at a temperature of -8˚C or lower[4]. A sustained temperature of -8˚C or lower in Canada usually occurs sometime between December and February, extending the harvesting season for Icewines into early winter and sometimes into early spring[4].

Certain grape characteristics are more desirable for Icewine, and care must be taken when choosing a varietal suitable for low temperature growing conditions. A white hybrid grape varietal (Vidal Blanc) is Canada's leading Icewine grape variety, as it ripens late and maintains hardiness during cold temperatures (a brand of Vidal Blanc Icewine can be seen in **Figure 1**). Grape clusters can stay on the vine after frost, and until up to 30% of their weight is lost to dehydration[2]. Vidal Blanc grapes can be harvested up to 40 days after reaching maturity and have thick skin, making them more resistant to cold temperatures and pests[2]. Beyond these appealing properties, the grapes are also readily available, easy to manage, and inexpensive to grow[2]. While Icewine production is truly an art culminating in a high-quality product, the current industry is not presently sustainable. Many factors impact Icewine production, and the rest of this article will discuss how climate change is one major force affecting the industry. The Icewine industry is poised to rapidly evolve as a result of climate change, and if Icewine practices do not shift synchronously with the environmental conditions, the industry may risk being lost altogether.

Figure 1: An Icewine made from Vidal Blanc grapes, which are a popular varietal for Icewine production due to their desirable cold hardiness, pest resistance, and availability[5].

TABLE 1: MEAN DAILY TEMPERATURE CHANGES IN THE NIAGARA REGION based on RCP 4.5 and RCP 8.5 scenarios in 2050 (average of 2040-2069) relative to present climate from historical data (average of 1986-2005) (Adapted from Deng et al., 2018).

Months	Present Climate (˚C)	2050 Temperature Changes (˚C)	
		RCP 4.5	RCP 8.5
December	-0.8	+2.3	+3
January	-3.8	+2.1	+2.8
February	-3.3	+2.8	+3.2

NIAGARA CLIMATE PREDICTIONS

The Niagara region is one of the leading producers of Icewine due to its ideal climate of hot summers and cold winters. The current winter climate is sufficiently cold to produce an Icewine crop every year[6]. However, will this change in the future with predicted global warming? To attempt to answer this question, one can analyze climate models.

Climate models use our understanding of Earth processes to predict temperature changes[7]. As various models can have different values based on their input parameters, climate scientists use a combination of several climate models called climate ensembles to account for these discrepancies between models. The Ontario Climate Data Portal provides climate projections from an ensemble of 209 climate models using the Intergovernmental Panel on Climate Change (IPCC) scenarios[7].

The IPCC scenarios are designed to give projections based on the representative concentration pathway (RPC), which are reliant on what year the global CO_2 emissions decline due to adapting climate policies and changing energy sources. The RCP scenarios are labelled based on the **radiative forcing** in the year 2100[8]. This value represents a change in the net radiation of the Earth, particularly how much solar radiation has been absorbed versus emitted into space. For example, RCP 4.5 indicates a radiative forcing of 4.5 W/m^2 in the year 2100[9]. The scenarios analyzed in this article are RCP 4.5 and RCP 8.5, which were chosen as they represent an intermediate and worst-case scenario, respectively[8].

Radiative Forcing: change in net radiative flux of the Earth.

The predicted temperature changes from the RCP scenarios were found for the longitude and latitude of the world's largest Icewine producer, Pillitteri Estates Winery, to represent the Niagara region, as climate is relatively consistent through the region[10]. The main Icewine harvest months were analyzed for changes in mean daily temperature in the mid-century for RCP 4.5 and RCP 8.5, as shown in **Table 1**. It was evident that in both RCP scenarios, the mean daily temperature would increase by 2˚C to 3˚C in 2050 with the greatest changes in the month of February[7].

IMPORTANCE OF CLIMATE ACTION

It is clear from **Table 1** that the temperature changes are greater in the RCP 8.5 scenario; however, the difference is not large. This is attributed to the fact that the radiative forcing in both scenarios increases at a similar rate into the midcentury. Nonetheless, for the RCP 4.5 scenario to occur, it is assumed that mitigation strategies for climate change will be employed to stabilize radiative forcing around 2050. On the other hand, the RCP 8.5 scenario is defined as "business as usual," meaning it describes a development where no climate action is taken[8]. The 2050 timeframe investigated in this article will likely not have climate impacts which result in Icewine production halting entirely, as the cold temperatures can still be reached in both RCP scenarios[7]. Since RCP 4.5 stabilizes at these temperature values, under this scenario, the Niagara Icewine industry will be able to produce Icewine for the foreseeable future. However, if the trend follows the RCP 8.5 scenario and there are no climate actions by the end of the century, the Niagara region may no longer be able to produce Icewine yields because the temperature may be too warm for consistent freezing. This demonstrates how critical the actions taken to mitigate climate change will be in the coming decades for the Niagara Icewine industry.

CURRENT CLIMATE CHANGE IMPACTS

Climate change may not be a pressing issue for Icewine production in Niagara at the moment, but wineries have already experienced some effects that are predicted to get worse.

NIAGARA CLIMATE TRENDS

Climate trends in the Niagara region can be examined to understand the current and future impacts of climate change. In 2010, Environment Canada analyzed changing climatic conditions in the Niagara region using the National Climate Data and Information Archive[11]. It was concluded that annual mean temperatures increased by 1.3˚C from 1961 to 2009, with greater increases in the winter months. The number of **extreme hot days** rose while the number of **extreme cold days** decreased from 1970 to 2009[12]. During these years, the number of extreme cold days decreased by an average of three days per year which suggests that there may not be enough days cold enough to harvest grapes in the future. Moreover, the average number of frost-free days has increased since 1970[12]. Frost-free days are consecutive days in a year that have a mean temperature over -2˚C. A rise in frost-free days can lead to a delay in harvest as grapes will not freeze if temperatures do not fall below -8˚C. In addition, freeze-thaw cycles have also been increasing. These cycles take place when daily temperatures fluctuate above and below the freezing point[12]. If warming continues, freeze-thaw cycles are expected to initially peak and then decline overtime[12].

Extreme hot days: occur when daily maximum temperatures are over 30˚C.
Extreme cold days: occur when the daily minimum temperatures are below -15˚C.

ICEWINE AND CURRENT CLIMATE

The exact relationship between climate change and Icewine is unclear. Despite the effects noted above, current climate trends have a negligible effect on current Icewine production, but they provide a warning about possible future impacts. The connection between climate change and Icewine can be anticipated by comparing current climate trends to the VQA requirements for Icewine production. The main threat of climate change is the increase in winter temperatures as grapes need to be naturally frozen and harvested at or below -8˚C[13]. The negative effects of warm winters were apparent following the El Niño event in the winters of 1997 and 1998. El Niño is a warming pattern caused by an increase in ocean temperatures in the equatorial Pacific. In the winter of 1997 and 1998 average temperatures increased by 6˚C in Southern Ontario causing the Icewine industry to experience a $10 to $15 million loss during this season[14]. Although the current effects of climate change are minimal, Icewine producers are aware that they will be amplified in the future.

WHAT DO NIAGARA WINERIES HAVE TO SAY?

With rising temperatures from climate change, Niagara wineries appear to have a range of responses to combat the changes, some more severe than others. Joe Will, the president, founder, and original winemaker of Strewn Winery in Niagara, was interviewed regarding the impact of climate change on their Icewine production[15]. He is unsure if the implications of climate change have directly affected growing practices so far. They have been making Icewine in Ontario for 50 years and have needed to change the machinery they employ for harvesting grapes but are unsure whether this change is related to warming weather or not. Will admitted that while Strewn Winery has never encountered a winter where they could not yield any grapes for Icewine, there have been a couple of years where only one night was cold enough for harvest. He continued to state that substantial warming could cause practices to change. Currently, the biggest issue that the winery faces is pests. Birds, especially starlings, gather into flocks of thousands in the winter months to feed on large portions of grapes within hours[15]. Additionally, if it does not get cold enough, grapes rupture, leading to berry fallout and subsequent feeding by birds.

Not only are pests becoming increasingly prevalent for Icewine producers, but the number of harvest nights are decreasing. An article published in 2012 by *The Star* stated that Niagara winemakers usually have an annual average of ten suitable nights for grape harvesting, but that year only five or six nights were sufficiently cold[16]. This resulted in lower yields and higher prices of Icewine to compensate for these losses. Jamie Singlerland, the president of marketing for Pillitteri Estates Winery, said that the mild temperatures led to additional growing weeks, allowing for riper and sweeter grapes which produced higher quality wine. Therefore, the warming temperatures caused Pilliterri to produce less, but better-quality Icewine at a higher price. In 2012, Pillitteri picked approximately 60% of their crops and produced half of what they originally planned for that year[16]. As well with warming temperatures, the harvest times have shifted, and fewer frigid nights have made the crop yield less predictable. To combat these changes, Pillitteri Winery have adopted mechanical harvesters that allow for the grapes to be harvested faster than that of a manual picker, an advantage if bad weather is looming. In 2002, temperatures dropped below -8˚C on only two nights resulting in workers from Pillitteri Winery rushing to harvest the grapes in time[17].

While some wineries may be experiencing hardships with rising temperatures, others are profiting off of them. Some Icewine producers believe that Icewine can benefit from the effects of climate change. John Warner, owner of Warner Vineyards in Nova Scotia, believes that Icewine grapes require freeze/thaw cycles to enhance the flavour. The fluctuation between warm and cold days allows oxygen to flow through grape skin and full fruit flavours can develop[18].

It may be difficult to attribute certain characteristics of current weather to climate change because it is a long-term process that can only be understood by studying patterns of past climate. However, there are some effects that we can see today that are just the beginning of more to come. For example, Anthony Shaw[19], a fellow of the Cool Climate Oenology and Viticulture Institute, discovered that the ideal number of picking days for Icewine grapes have been on a gradual decline in Ontario since the 1980s[19]. Shaw argues that although "it's not a drastic situation right now", persistence of climate change will impose several threats on the Canadian Icewine industry[19]. Moreover, implications from climate change might not be evident to wineries currently, but research indicates that this is just the beginning of a tough battle with climate change.

Eiswein: Unlike Canadian Icewine, German Icewine, or 'Eiswein', production has already been impacted by changes in climate. The country where Icewine originated can now barely produce their renown wine due to global warming[20]. Recent decades have experienced severe climate warming, delaying the Eiswein harvest dates and leading to uncertainty in the industry. Moreover, climate predictions only depict further warming in the German wine regions, painting an even bleaker picture of the Eiswein future[20]. The year 2019 marked the first year without a German Eiswein vintage since the wine was first documented in 1830[21]. As Ontario is predicted to experience warmer temperatures, it is crucial to ask whether the Niagara Icewine industry will have the same fate as German Eiswein.

FUTURE CLIMATE CHANGE IMPACTS

Since it is likely that temperatures will still be able to reach the requirements for Icewine in 2050, the main concern is the delay of the first frost event. This can lead to grapes staying on the vines for a much longer duration and decrease Icewine crop yields. As discussed, in the Niagara region, Icewines are typically harvested between the end of December to the middle of January[22]. Warming in December and January, indicated by the values in **Table 1**, can potentially push this harvest window into February or even March[7]. This may force growers to harvest non-frozen grapes for late-vintage table wines[23]. In contrast, those who wait until optimal conditions to harvest may encounter additional risks.

As grapes remain on vines longer, there may be crop loss due to wind, predation and rain-related diseases such as rot, with thinner skinned varieties at more risk.

For example, noble rot is an infestation by a fungus called *Botrytis cinerea* that can colonize grapes and dehydrate them. This can decrease the yields to negligible portions and prevent freezing from occurring[22]. Warming weather is expected to increase the amount of freeze/thaw cycles. As discussed earlier, vineyards welcome the current increase in freeze/thaw cycles since it is ideal for rich Icewine flavour. However, with a greater abundance of freeze/thaw events, these cycles can impose mechanical stress on certain grapes, causing them to rupture and become more susceptible to rot diseases and colonization by opportunistic bacteria[4].

The risk of a delayed Icewine harvest is further exacerbated by the fact that warmer temperatures also coincide with earlier maturity[24]. Bird predation will increase as these pests have reduced food sources in the winter and are attracted to the ripe grapes hanging on the vines. A warmer winter will also limit the migration of some bird species, such as starlings[14]. Other potential predators, such as deer, racoons, and coyotes, can become threats to grapes in the winter season for similar reasons[22]. Predators are more likely to enter pest infested vineyards, hence, the influence of pests must be considered. A rise in temperature and milder winters will make the Niagara region more habitable for insect pests. Some species such as *Paralobesia viteana* (grape berry moth) will thrive in warmer conditions by being able to increase reproduction (**Figure 2**)[25]. Allan Jackson, owner of Jackson-Triggs Estate Winery, expressed that he has not noticed an increase in pests but rather an emergence of novel species of pests in his vineyards. Jackson explained that in 2001 there was a large issue with *Harmonia axyridis* (Asian lady beetle) infestation in vineyards (**Figure 2**) which was a "harbinger of climate change issues"[26]. This is because the Asian lady beetle emerges in warm, sunny climates and their increased activity in vineyards is likely due to temperature rises. This can be an indication of possible issues that can threaten the Icewine industry due to climate change.

Overall, it is important to recognize that this relationship between climate and Icewine may not be as straightforward as discussed. There will be climate fluctuations every year, as the temperature does not increase linearly and will change from year to year. Regardless, on average, the climate will warm in the long run and eventually affect the reliability and consistency of Icewine production. The extent of these impacts will depend on international climate action. In the meantime, it is essential to understand what the Niagara Icewine industry can do to mitigate these climate-related effects.

Figure 2: *Paralobesia viteana* (grape berry moth) on the top[27] and *Harmonia axyridis* (Asian lady beetle) on the bottom[28].

ADAPTATIONS IN THE INDUSTRY

A plethora of research has been conducted to investigate adaptations that the table wine industry is making to mitigate the effects of climate change. Though there is less research focused on the effects of climate change on Icewine grapes, as the market for Icewine is much smaller, research on table wines can be applied to the Icewine industry with knowledge of the differences and similarities in Icewine growing. This section will discuss adaptations addressing the projected climate model effects in the Niagara region. The predicted increase in temperature could negatively affect Icewine production by forcing grapes to be on vines for an extended period, thereby increasing their likelihood of contracting a pathogen or over-ripening. Here we will provide an overview of the seemingly two outcomes possible for the industry: technological adaptation, and vineyard movement or termination.

TECHNOLOGICAL ADAPTATIONS

GENETIC ENGINEERING

Genetic engineering is a prominent technique used in agriculture to manipulate organisms to express the most advantageous phenotypes. One-way genetic engineering can be used is to make plants more resistant to certain diseases and/or conditions. Genome-wide association studies can be used to determine which genes are problematic in grapevines and should be later targeted for genetic engineering. These types of studies can effectively be carried out in wine, as the genome is a relatively small 480 million base pairs long. Approximately 41% of the wine genome is repetitive, and most wine genomes are diploid (two chromosomes, thus two copies of one gene), meaning they are simple to edit[29]. Transgenic grapevines have been successfully cultivated since 1985 and continue to positively influence grape taste and plant outcome. Programmable nucleases are different biological vessels that can be manipulated to edit genes. These nucleases can cut DNA and double-stranded break at targeted sites[29].

One of the most widely used programmable nucleases is the CRISPR-Cas9 system. A CRISPR-Cas9 system is a gene-editing tool that can cut out and replace problematic genes in DNA[29]. A novel study is using CRISPR-Cas9 to alter the NJ76 Chardonnay genome by taking out the VvHSK and VvF3DOL genes. These genes were identified to contribute to making this plant more susceptible to downy mildew disease[30]. Investigators in this study will be analyzing gene-edited plants versus regular NJ76s to determine whether there was a significant effect on disease resistance[30]. The CRISPR-Cas9 system has high potential in the Icewine industry as it can take out genes related to heat sensitivity and input ones that make the stress response more resilient to heat. The system is also able to make plants more adaptable towards pests and fungal attack.

ARTIFICIAL FREEZING

If in the future Canadian winters do not have enough cold weather days for proper Icewine maturation, one potential solution could be artificial freezing. Artificial freezing is a method already used in countries that are too warm to produce natural Icewine conditions. In artificial freezing, wine grapes are harvested when they are partially but not completely ripe ~26˚ to 30˚ Brix and are frozen in a deep-freezing chamber[4]. Where one degree Brix is equivalent to one gram of Sucrose in 100 grams of solution[4]. Apart from evading non-ideal weather conditions, artificial freezing also prevents grapes from over-ripening and damage due to the increase in pests.

FUTURE PREDICTIONS

MOVEMENT OF GROWERS

Though the effects of climate change may prove to be severe, this does not mean that the growth of Icewine and other sensitive table wine varieties need to stop. Viticulturists have used climate outlooks to propose novel growing locations that will soon be favourable for specific varietals based on temperature[3]. Considering the temperature-sensitive nature of Icewine production, this is the type of proactive approach that will make the difference between growth and detriment to the Icewine industry. If the increased temperatures prevent the Niagara industry from maintaining the -8˚C to -12˚C temperature range, then it might be wise for vineyards to move North to regions that used to hold temperatures too cold for cultivation. Though there is no current literature that suggests specific locations, Vancouver Island could be an excellent option with a variety of fertile soil types as well as many areas of higher elevation and thus cooler temperatures[32].

WILL OUR STANDARDS CHANGE?

A final facet of change that may occur for the Icewine industry within the scope of climate change is the potential for change in the official VQA standards for what temperature ranges qualify for Icewine[6]. In fact, other countries such as Germany have higher temperature standards than Canada for what qualifies as Icewine (in Germany's case the temperature conditions are -7°C)[3]. Another component of the VQA which is likely to change, as discussed earlier in this article, is the qualification of Icewine with regards to artificial freeing. Currently, the VQA does not consider artificially frozen grapes eligible for being Icewine, however, with temperatures on the rise, artificial freezing may be an efficient and less risky option for the future of Icewine production[6].

PREDICTIONS FROM A WINE-MAKER

According to viticulturist Will Roman of Niagara's Rosewood Winery, many of these technological adaptations may not be an economically feasible option for most growers[33]. Roman argues that for winemakers to completely pack up shop and move, they would first need to invest three to five years in growing and training vines to grow to a certain configuration. He also predicts that since the demand for Icewine has decreased over the past couple of decades, due to a decrease in user interest, vineyards are more likely to either stop their Icewine production or significantly decrease it in the near future[33]. However, since Niagara is one of the primary producers of Icewine worldwide, he does anticipate that the industry will not completely die out[33].

CONCLUSION

Throughout this article we have delved into the current and possible effects that climate change may have on the Icewine industry in the Niagara region. After analysis of current and future impacts of climate change, the connections between climate change and the Icewine industry are clearer. Although Icewine practices are not currently being detrimentally affected by climate change, the increasing temperatures will likely challenge Icewine growers as time goes on. Our interviews with Icewine producers show that they are aware of the ever-changing conditions and the possibility for the need to adapt their practices in the near future. Our goal is for our report to act as a motivation for Icewine producers to anticipate more drastic changes in the future, and as encouragement to have a proactive approach to managing these effects in order to avoid potential fallout of the industry. Overall, we hope for this article can be used as a comprehensive analysis on the Icewine industry, focusing on the connection between Icewine and climate change, both present and future. Climate change will continue to grow as a threat to the Icewine industry, and we are hopeful that reports such as this can contribute to plans to mitigate these effects in order to preserve the Niagara Icewine industry.

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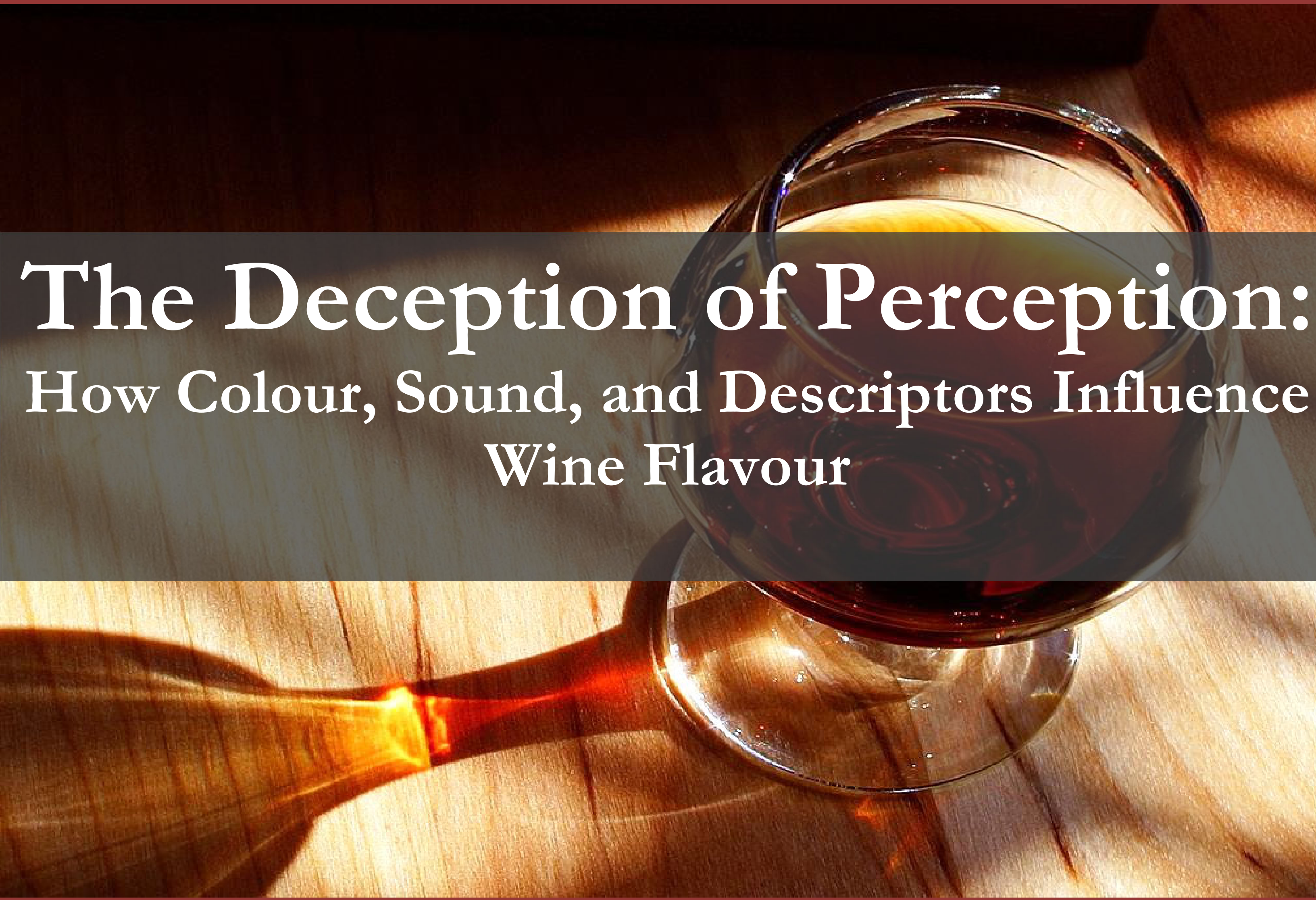

The Deception of Perception: How Colour, Sound, and Descriptors Influence Wine Flavour

Saif Alam, Kristen Arnold, Chantelle Castelino, Anna Morley, Sarah Watson

How do we define the flavour of wine? A variety of intrinsic factors, from temperature to alcohol percentages, impact how we perceive the complex taste of wine. But what if this perception could be changed by more than just intrinsic factors? What if the music, dim lighting, or waiter accouncing that your Syrah is from the Côtes du Rhône all act to manipulate the taste of your wine?

This article explores how external cues, like those present at your favourite restaurant, can completely change wine flavour perception. So pour yourself a glass as we dive into the deceptive world of perception biases!

WINE PERCEPTION

Wine is an inherently complex, multisensory-stimulus product, and our perception of its taste and quality are influenced by a multitude of contextual factors. Traditional wine research has focused on viticulture and oenology; only in the past few decades has research begun investigating the role of external environments and related cues in wine perception[1]. With a growing body of evidence suggesting that our perception of wine is heavily influenced by external factors such as colour, audition and wine descriptors, this prompts us to ask the question: is wine tasting as objective as we initially believed it to be? Further, what implications does this evidence have for the wine industry? In this article, we investigate how wine colour, background music, and wine descriptors bias our perception of wine flavour.

TASTE THE COLOUR

The appearance of a particular food or beverage can widely influence an individual's perception of its flavour. Colour is one of several **extrinsic factors** that influence one's perception of edibility, intensity and flavour recognition[2]. As Clysdale[3] proposes, colour does not simply hold aesthetic value[3], but rather, it is one of the many factors that contribute to our multisensory flavour perception. The concept of colour itself is a social construct, as each individual interprets colour with a certain degree of subjectivity[2]. In a study carried out by Shankar et al.[2], British and Taiwanese participants were given a brown coloured beverage to taste. Prior to tasting, the majority of British participants affiliated the colour of the drink with a "cola" taste, while the majority of Taiwanese participants affiliated the same colour with a "grape" taste. This study lent insight into the preconceived affiliation between colour and taste, whereby colour helped shape the individuals' expectations prior to the consumption of the beverage. This preconceived notion, called priming in psychology, results when an initial stimulus impacts how an individual responds to a subsequent stimulus[4]. In this case, colour was the initial stimulus, which primed the participants to have a certain taste expectation for the beverage.

Extrinsic factors:
A property that is not inherent or essential to the object

As it relates to oenology, wine offers the richest range of colours than any other class of beverage in the world.[1] From a tawny port to a sparkling rosé, the colours and shades of wine are diverse and complex. These varying hues impact the manner in which an individual is able to perceive the beverage they are tasting. Within this context, top-down processing (Figure 1), another important cognitive process, plays a central role in many studies examining the impact of colour in the wine industry, namely, understanding its influence on wine perception[5].

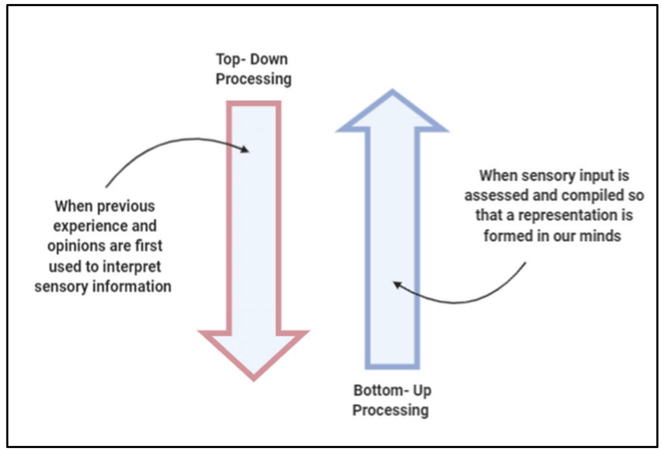

FIGURE 1: COGNITIVE PROCESSING. Differences between top-down and bottom-up processing in response to stimuli (adapted from Zoghbor[5]).

In a study by Morrot[6], researchers aimed to assess whether untrained participants would misidentify a wine when its colour was altered. Participants were asked to describe the aroma and flavour of a white wine dyed with an odorless red dye. Based on both the aroma and the flavour, all the participants mistakenly described the white wine as a red wine. This result indicates that colour played a critical role in wine identification within this sample of participants[6]. Through this study, Morrot illustrates a prime example of top-down processing and how participants identified the wine samples based on their preconceived association between wine colour and aroma. This example of misidentification is a perceptual illusion, as the participants had been primed to affiliate the colour of a particular wine with a certain flavour. Not only does this study demonstrate colour as being a significant factor in identifying wine flavour, but it also also showcases how individuals can be primed to expect certain attributes when presented with a specific colour[6].

In a similar fashion, Parr, White and Heatherbell[7] built upon the Morrot study and looked at colour-induced olfactory bias in wine experts. In this study, the experimenters prepared four wine samples: an unaltered white wine, a white wine artificially masked as gold with caramel and tumeric, a white wine artificially masked as red with anthocyanins, and an unaltered

red wine[7]. Wine experts were presented with 16 samples of wine; a total of eight samples in clear glasses with the remaining eight in opaque glasses. The purpose of the clear glasses was to test the impact of a visual cue whereas the opaque glasses were designed to prevent the presence of any colour-induced bias[7]. The authors found that wine experts displayed colour-induced olfactory bias and were in fact influenced by the masking of the white wine with anthocyanins when the red colour served as a visual cue in clear glasses. This illustrates a cognitive model wherein wine experts used top-down processing to help classify the wine samples by comparing their colours to prototypes that they had previously seen before.

Additionally, another study conducted by Wang and Spence[8] supported the idea that wine experts use top-down processing when trying to identify wine samples. This study compared the effect of colour among wine experts and revealed further evidence to suggest that even the most experienced connoisseurs may succumb to the interplay between colour and perception[1]. In this experiment, a total of 168 participants were tasked with describing the flavour and aroma of three unique wine samples: an unaltered white wine, a rosé wine, and a white wine artificially dyed to resemble the rosé (Figure 2). The authors found that participants with a previous background in wine tasting incorrectly characterized the flavour and aroma of the artificial rosé by using descriptors similar to that of the rosé, rather than those of the white wine thus, highlighting how top-down cognitive processes are able to hinder the ability of even the most experienced experts[8].

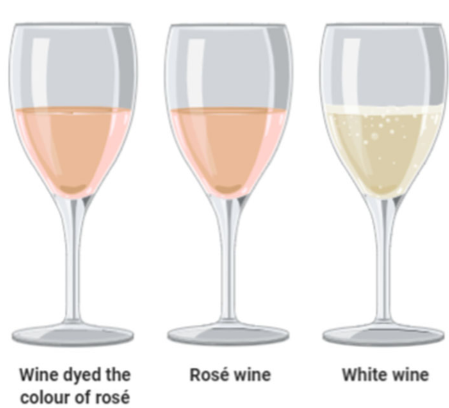

FIGURE 2: EXPERIMENTAL DESIGN. Three wine samples presented to participants in the study conducted by Wang and Spence[8]. This includes a white wine, a rosé, and a white wine dyed to look similar to a rosé (adapted from Wang and Spence[8]).

TASTE THE MUSIC

According to wine writers and bottle labels, wine may have citrusy "notes" or perhaps a "harmonious" blend of oak and vanilla. While these seem to be merely figurative expressions, recent research is suggesting that music and taste are more closely linked than previously imagined.

Cross-modal Correspondence: Associations between features or attributes of one sensory modality (e.g. audition) with those of another modality (e.g. taste)

Auditory and musical influences are extrinsic cues that can have a substantial effect on consumers' perception of a wine's flavour. These cues can include pre-recorded or live music and sounds of varying frequencies. Many studies have delved into the **cross-modal correspondence** between taste and audition, specifically how background music can affect the perception of wine flavour[1,9]. A study by North[10] selected four pieces of music that were classified by a preliminary panel as being: (1) zingy/fresh, (2) powerful/heavy, (3) mellow/soft, or (4) subtle/refined. They had non-trained participants sample a glass of wine with one of these songs playing in the background. Participants were asked to rank how well the wine corresponded to each of the four descriptors above. Overall, when the zingy/fresh song was playing in the background, participants ranked the wine as being more zingy/fresh. And when the powerful/heavy music was played, participants ranked the same wine highest for the powerful/heavy descriptor. A similar study from 2019 probed further by asking participants how many different wines they thought they had sampled. Although the participants had been given the same string of beverages two times in a row, due to the change in music for each string, they had not recognized the repetition[11]. It is amazing that changes in background music altered the perception of wine to such an extent!

While North's study had participants drink their wine over several minutes as the music played, a study by Wang, Mesz and Spence[12] siphoned down the experiment to a single 30-second sip. Specially designed soundtracks switched from "sweet" to "sour" or vice versa while the participant held the sip of wine in their mouth. Researchers were able to measure the change in participants' rankings of sweetness or sourness of the wine in relation to the change in the soundtrack. They found that even within 30 seconds, the evolution of the music led to predictable changes in the perception of wine flavour.

Music is a complex construct of notes and melodies prone to differing individual interpretations. When attempting to pair wine with music, if the music's message is not interpreted as intended, it would not have the desired effect on one's perception of wine flavour[10]. Consequently, to assess whether there exists a more universal effect of audition on wine perception, Burzynska et al.[13] focused on the pitch or frequency of sound. They found that listening to low pitched sounds while drinking red wine increases the perceived body and aromatics of the wine, producing a heavier mouthfeel.

Interestingly, research has shown that groups of people tend to agree on how well certain songs or sounds 'match' with specific flavours or aromas in food or wine. Studies have found that sweetness, sourness or fruity flavours correspond to higher pitches and the sounds of piano or woodwinds[14, 15]. On the other hand, smoky, woody flavours and bitterness match with lower pitches and brassy instruments[14,15]. Spence et al.[16] looked at pairing wines with classical music pieces and found that Tchaikovsky's String Quartet No 1 in D major was ranked as a very good match for the red wine, Château Margaux 2004, for example. Clark Smith, winemaker and founder of the wine consultancy company, Vinovation, states, "Red wines need either minor key or they need music that has negative emotion. They don't like happy music. [...] Pinots like sexy music. Cabernets like angry music"[1,17]. The associations between musical styles or sounds and wine seems to be more than a matter of individual taste. Wines will actually be rated more favourably when paired with congruent or matching music[16]. One possible theory is that when there is congruence between external stimuli, such as taste and music, the brain is better able to 'understand' and process the stimuli. This concept is called processing fluency[18].

> "Red wines need either minor key or they need music that has negative emotion… Cabernets like angry music."
>
> *— Clark Smith, founder of Vinovation*

The connections between music and flavour perception may also be explained by emotions. Both listening to music as well as eating or drinking can affect our mood. It is possible that a hedonic response to a piece of music – either really liking it or not – would transfer over to the completely unrelated stimulus of tasting a wine[18]. Emotion may also contribute to the degree of congruence between specific wines and pieces of music. A study by Wang and Spence[19] had participants pair three different red wines to three different musical selections and then make separate ratings on the emotions elicited by each wine and

WINE-MUSIC PAIRINGS

The innovation potential of this research is huge. "Food and wine" pairings are making way for the new "music and wine" pairings. In Christchurch, New Zealand, the Auricle Wine and Sound Bar creates a wine list each month to match music on exhibit at the adjoined Auricle Sonic Arts Gallery[18]. But you don't need to travel the world to explore music-wine pairings. The Champagne company Krug has created an app that can scan one of their bottle labels and provide customers at home with a playlist to suit the bottle[18]. Winemaker Clark Smith has also curated a list of songs to go with particular wines (Table 1)[9].

In the restaurant setting, some problems must still be overcome for music-wine pairings to really take off. For instance, how can you curate an appropriate playlist when diners at neighbouring tables are drinking different wines? One possible solution would be to use hyper-directional loudspeakers that play different music to each table. An alternative but equally over-the-top solution would be to serve wine in "digitally augmented glassware", which plays music that can only be heard when the glass is raised up for a sip[18].

Regardless of where this research leads in the future, perhaps you will think twice about selecting the playlist for your next dinner party…

each musical piece. These emotion ratings included the pleasantness or unpleasantness of the wine or music and the strength of the emotional response. Amazingly, blind reviewers could actually predict a participant's wine-music pairing by looking only at whether the wine and music in question elicited similar emotions[19]. This suggests that emotion plays an important role in mediating the cross-modal associations between music and wine flavour.

TABLE 1: WINE MUSIC PAIRINGS. A selection of Clark Smith's wine-music pairing recommendations[9].

WINE	RECOMMENDED MUSIC PAIRING
Carneros Pinot Noir	"Eine Kleine Nachtmusik" – Mozart
Cabernet Sauvignon	"People are Strange" – The Doors *Carmina Burana* – Carl Orff
Sutter Home White Zinfandel	"Milorganite Blues" – North Water Street Tavern Band
Glen Ellen Chardonnay	"California Girls" – The Beach Boys
Rombauer Carneros Chardonnay	"St Louis Blues" – Ella Fitzgerald

TASTE THE LABEL

Descriptors refer to an informational cue that may serve to influence or guide a consumer's interpretation of the perceived quality of a product during tasting. It is not difficult to understand how these cues inevitably influence consumer purchasing behaviour. However, descriptors can unconsciously alter an individual's judgement of perceived quality and taste, thereby influencing consumers far beyond the initial purchase of a product!

Disclosing the procedures used to create a wine can disrupt or enhance the sensory experience, depending on how the processes are stigmatized. Labelling a wine as being genetically modified disrupts the sensory experience during consumption such that these wines are perceived as having less favorable appearance, aroma, and taste compared to wines without this label[20]. Consumers also view the quality of the wine to be lower and it decreases likelihood of repurchase[20]. In contrast, when wine is labelled as organic, the sensory experience is enhanced, and this label actually increases the wine's perceived taste and texture relative to unlabelled wine[21]. While most people like to believe that external cues do not influence their flavor perception, one type of **cognitive bias** is very much present when consuming wine. The cognitive process that is likely responsible for this enhanced perception is called the halo effect[20,21]. This effect refers to when a general impression of a person or thing is applied to an unknown attribute, unconsciously altering an individual's overall judgement[20]. This phenomenon is visually depicted in Figure 3[22]. In these cases, the participants' preconceived notions about genetically modified versus organic products influences their perception of the quality and taste of the exact same wine! Genetic modification acts as a negative stimulus, creating a negative halo effect. On the other hand, the organic wine label acts as a positive stimulus, creating a positive expectancy driven halo effect, which enhances wine perception positively, as opposed to the negative effect seen with genetic modification labelling[20,21].

Cognitive Bias:
A psychological concept first proposed in 1974 that explains a systematic error in thinking which influences our perception of the world, judgement and decision making.

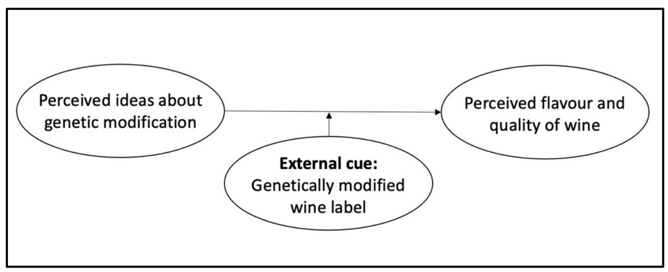

FIGURE 3: HALO EFFECT. A diagram showing how an external cue (in this case, a genetically modified wine label) contributes to the already existing ideas about genetic modification to influence the perceived flavour and quality of the wine (adapted from Her and Seo[22]).

Price and country of origin are very common descriptors that consumers rely on to judge the quality of a wine product. While higher price labeling has been shown to enhance quality perception,[23,24] it has further been shown to actually override poorer tasting wine[25]. In other words, wine that tastes objectively worse due to the addition of acid, but is marked at a higher price, has a higher quality rating than untreated wine simply due to the higher price label[25]. Similar findings have been found when considering countries of origin. Country of origin is always displayed on a wine bottle label (Figure 4). 'Country image' is the term used to describe a country-specific profile that is constructed using psychological associations between various

JUDGEMENT OF PARIS, 1976

Because of the complex history of viticulture on an international level, country of origin unsurprisingly influences our perception of wine. One of the most important demonstrations of this phenomenon was the 1976 tournament known as the 'Judgement of Paris'. Although this event's findings did not garner much attention at the time, the significance of this demonstration has been realized over the past 40 years. In a blind tasting event where French judges evaluated French and Californian wines, the Californian wines surprisingly beat the French wines, despite France being generally regarded as the top producer of the world's best wines[26]. While the monopoly that France held on the wine industry has since faded, recent studies still show the dominant effects of the French 'country image' on wine perception!

information sources[25]. Examples include knowledge of products produced by this region and economic strength[25]. Price and country of origin create expectations for the consumer, which are both powerful enough to overcome sensory perception of the wine and enhance or reduce quality and flavor perception, depending on the labeling[23–25]!

FIGURE 4: COUNTRY IMAGE. Although these bottles share similar deisgn features, such as the red capsule colour and beige labelling, the bottle on the left is a wine made in France and on the right, in the United States.

The information obtained from a wine label clearly has effects on wine perception, but what about the *way* in which this information is presented? A study by Gmuer, Siegrist and Dohle[27] investigated the role of processing fluency on **hedonic ratings** and found that wine labels with high processing fluency positively influenced the hedonic taste rating, and low processing fluency negatively influenced the hedonic taste rating. In other words, the easier it is to read a label, the better the wine tastes to the consumer. These results suggest that our perception of wine taste extends far beyond the descriptor cues we observe prior to tasting and actually relies on the ease with which we can understand these cues[27]. This shows the inherent complexity of wine as a product, which inevitably adds difficulty to its quality assessment.

Hedonic rating:
Scale method to measure food or drink preference

SO WHAT?

So what does all of this research mean for consumers, restaurant-owners, and wine makers? Well, for one thing, it tells us that we're not as good at "objectively" tasting wine as we might have thought. There are so many external factors that influence how we perceive the flavours of wine. The colour of the wine, the music playing in the background or contextual information all create expectations of what the wine should taste like. This top-down processing – generating preconceived expectations about a wine from external cues – can lead to completely different perceptions of the same wine. These findings drive home the importance of how a wine is presented and/or displayed. The fact that visual cues influence perception is also applicable beyond the wine industry, for example with food presentation and fine dining (Figure 5)[28].

Emotions and mood can also play an important role in how we perceive the taste of wine. The Chardonnay you enjoyed so much in Cancún may not taste as amazing served at a work function back home. Choosing music at a dinner party that guests enjoy will likely buoy the general mood and enhance the food and wine experience.

A. "Painting #201" by Kandinsky.

B. Kandinsky-inspired artistic presentation of food.

FIGURE 5: BEYOND THE WINE INDUSTRY. Visual cues, such as presentation of food, may also influence perception of taste and enjoyment of the dish. Here, a chef was inspired by an abstract painting by artist Kandinsky to arrange salad on a plate[28].

It turns out that music has a much greater impact on our perception of wine that previously imagined. A new concept called sonic seasoning has been born from the fact that congruent music enhances wine flavours[1]. Just like how we use salt, pepper or spices to season food to our individual taste, music could be used to make a wine more enjoyable for different people. For example, by playing "sweet" music the astringent tannins in a wine can be downplayed. Since both wine and music preferences are highly personal, sonic seasoning could be effective for maximizing individual enjoyment[1].

In terms of the effect of colour on wine taste, there have been a few studies that investigate the effect of lighting as a masking technique. Since we now know that coloured environmental lighting may influence the perception of a wine, restaurants or wineries may opt to choose neutral, white lighting to allow for the most accurate tasting of the wine. This would ensure that consumers taste white wines as being white, red wines as being red, and so on. Moreover, the effects of lighting could have interesting implications for how people may perceive the taste of wine and other alcoholic beverages in bars or nightclubs, which typically have either dimmer or flashier lighting.

The research into descriptor label biases could have implications for wine tastings or winery tours. How much information about a wine should be provided prior to a tasting? As previously discussed, research has shown that consumers will rate the same wine differently if being presented with the price before or after the tasting[23]. Findings like these further emphasize the importance of blind tastings to obtain consumers' true opinions of a wine.

With visual, auditory and informational cues always present, what are you really tasting when the wine touches your lips? Sure, you taste the wine, but you also taste the colour, music, and label. Wine tasting is much more of a multisensory experience than initially expected. In some situations, perception being influenced by extrinsic factors may be a good thing, as they may help uplift the consumer's mood and therefore increase their liking of the wine. In others, such as professional wine tastings, having a more neutral setting may be beneficial to ensure more "objective" ratings of the wines.

So, the next time you pour yourself a glass and sip on your wine–whatever flavour it may be–think about what you're really *tasting* as you enjoy!

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Smoke Gets in Your Wines:

The Effect of Smoke Taint in Wine

Spencer Arshinoff, Grace Horseman, Helen MacDougall-Shackleton,
Maxwell Rival, Jessica Wassens

Recent wildfires have ravaged important winemaking regions, such as California and Australia. Based on complex interactions of human and environmental factors, their frequency will only increase in the future. The largest economic damage to winemakers is caused by smoke from these fires sweeping across fields of wine grapes and altering their chemical composition, which produces a "smoke taint" in the resulting wine. Smoke taint is characterized by a range of negative flavours and aromas such as "ashy" and "medicinal", although it may express itself differently based on the timing of smoke exposure and specific grape cultivars. Many strategies to mitigate the effects of smoke taint have been developed, from preventative measures, to post-harvest filtration, to the "masking" of undesirable flavours in the final wine. The devastating economic impacts of wildfires, from direct spoiling of wine via smoke taint to their effect on wine tourism, pose a burning question – will the wine industry go down in flames or rise from the ashes?

INTRODUCTION

Fire is an integral part of many ecosystems, affecting aspects of climate, biogeochemical cycling, and vegetation distribution. Today, in places like Australia and California, we see the destructive impacts of wildfires on human society through social media and the news. Beyond the deaths, injuries, and destruction of property, these fires impact human lives in many other ways. One such aspect is wine. Smoke from these wildfires washes over vineyards, producing "smoke-tainted" wines. These wines have undesirable sensory characteristics, which impact marketability. In regions where wine production contributes significantly to the region's economy, understanding how to mitigate smoke exposure, remove smoke taint, and assess potential economic losses is critical. Before this, however, viticulturists and businesses must consider regional fire regimes to determine the risk of smoke exposure. Are these fire regimes impacted by climate change? How may winemakers prepare for these changes?

WILDFIRE AND WINE

In early October 2017, approximately 250 fires scorched the Northern Coast Ranges and parts of northern Sierra Nevada, California. Known by some as the Wine Country wildfires, these blazes included the Tubbs Fire (the most destructive fire in Californian history, and second most deadly) as well as the Nuns and Atlas Fires[1], which heavily impacted Napa and Sonoma Counties. These fire events cost the wine industry over $9 billion USD[2]. Along with the destruction of several thousand structures, the smoke from these fires severely degraded air quality in the San Francisco Bay Area. Following the ignition of many fires on October 8th, Wine Country regions to the north of San Francisco experienced AQI values of 151-200 (unhealthy) and 201-300 (very unhealthy) (**Figure 1**). Poor air quality continued to be reported in these regions over a week later[2].

Air on the Side of Caution – Air Quality Index:

Air Quality Index, or AQI, is based on the observation of particles 2.5 μm and smaller. The AQI scale ranges from 0-300+ and is broken down into six categories that represent air pollution levels from good (0-50) to hazardous (300+)[2].

Fires of this intensity are not uncommon in California, and even wildfires sparked by Diablo winds, such as the Wine Country wildfires, are not unprecedented for the region. Many converging factors impact the severity of wildfires, making it difficult to attribute these events to any one thing, such as climate change. Changes to weather and human social behaviour, and human population increase all play a part in shaping wildfire patterns[3,4]. In coastal California, increased

Winds of Change – Diablo Winds:

Diablo winds are strong, dry offshore winds that are most frequent during the fall and early winter. On October 8th, 2017, Diablo winds caused the Wine Country fires to rapidly increase in size and spread across the landscape. Recorded northwest of Santa Rosa, CA, the wind gusts reached speeds of 128 km/h, making these the strongest winds recorded at this site since 1993[2].

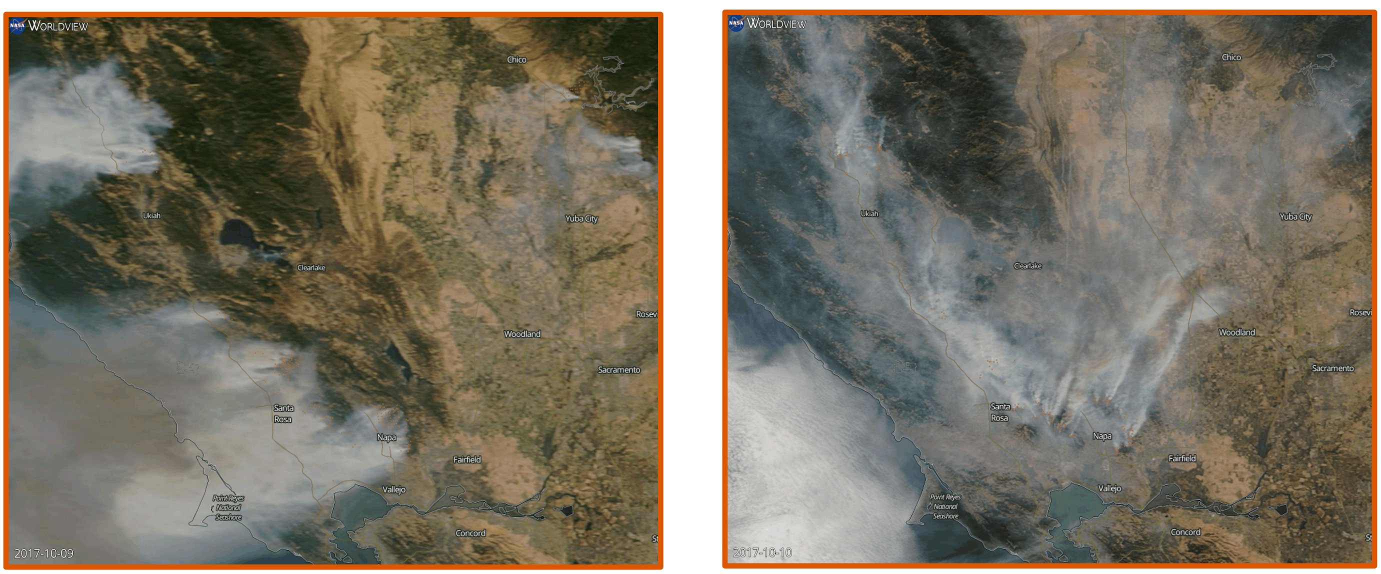

FIGURE 1: THE BIG SMOKE NASA Worldview (https://worldview.earthdata.nasa.gov/) true colour images showing drifting smoke over northern California on October 9th (left) and 10th (right), 2017. The smoke spread quickly and washed over several cities, impacting the health of residents.

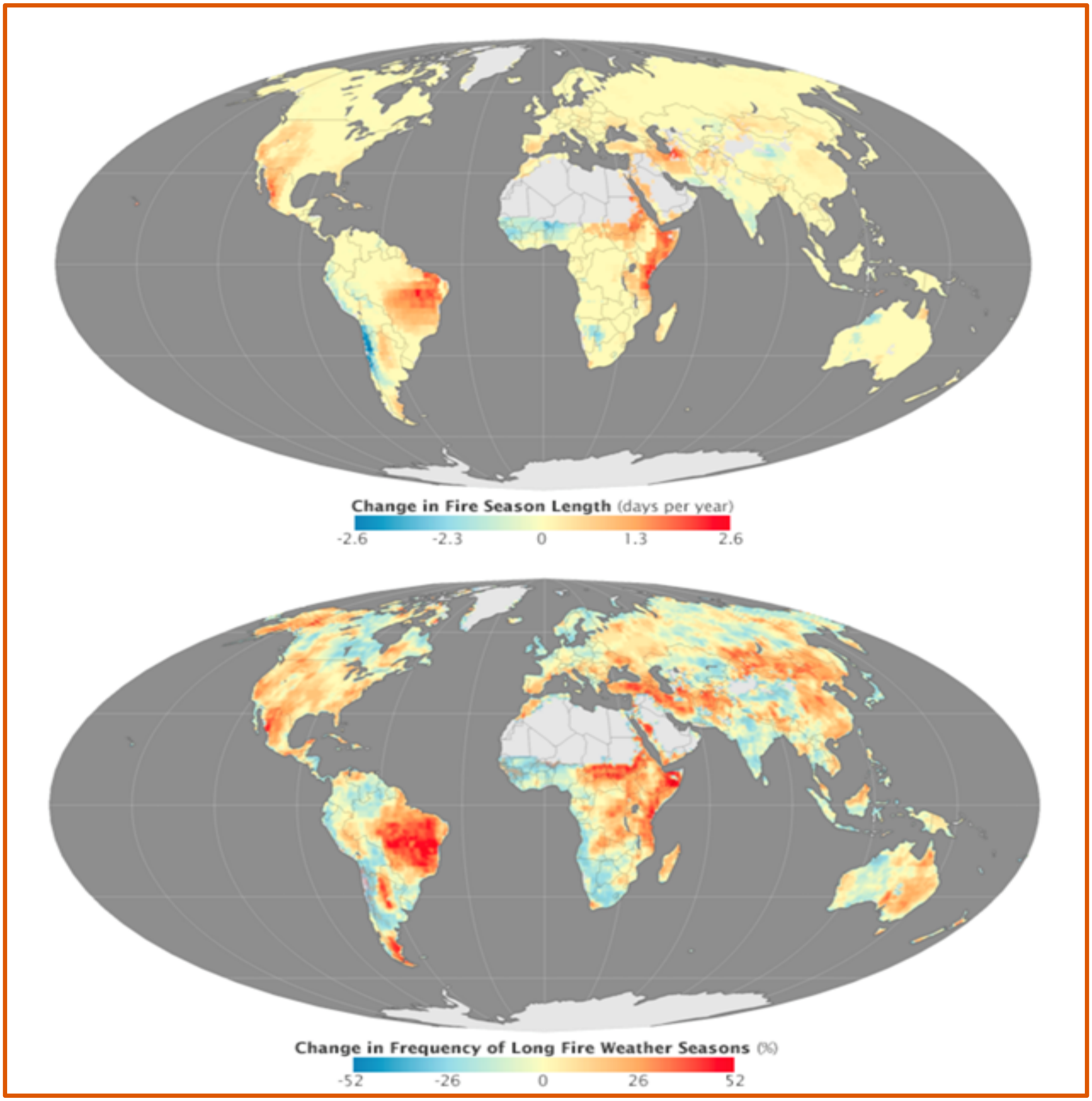

FIGURE 2: IT'S GETTING HOT IN HERE Areas of the world that show significant changes in the length of fire seasons observed from 1979-2013 (top) shown alongside areas that show a significant change in frequency of long fire weather season events observed from 1996-2013 (bottom). "Long fire weather season" is defined as a length one standard deviation from the historical mean[5]. These maps were created by Joshua Stevens, using data provided by Matt Jolly, USDA Forest Service.

winter precipitation can encourage the growth of herbaceous fuel like grass, which when dry increases the likelihood of fall wildfires – this occured in the 2017 Wine Country wildfires[2]. California, along with other parts of the western US, has experienced earlier snowmelt, and changes to precipitation patterns due to increased temperatures that are likely contributors to the lengthening of wildfire season (**Figure 2**)[4]. 2017 also marked the end of a five year drought that killed millions of trees and weakened others that were later killed by beetle outbreaks[4]. Changes to forest and grassland composition and density are not only due to short- and long-term weather conditions; human activities, such as intense prescribed burning and fire suppression practices, and changes to building materials used in infrastructure are also associated with wildfires[3]. The complex interactions between the human and natural landscapes make it difficult to predict how climate will change and how exactly fire severity and frequency will be impacted[2]. Despite this lack of certainty, it remains that fires are an economic and health concern. In late September 2020, another large wildfire much like those in October 2017 erupted in Wine Country proving wildfires to be an ongoing challenge for the US wine industry[6].

The US wine industry is not alone in this struggle against wildfires. Wine regions such as southeastern Australia, the Western Cape province of South Africa, and the Central Valley region of Chile also face the threat of wildfires to their vineyards. Global trends indicate an overall increase in the length of fire seasons and their frequency (**Figure 2**), with the exception of Australia which demonstrates regional variability[7]. South Africa's montane shrublands exemplify this trend, demonstrating persistent increases in fire weather season length (**Figure 2**). These shrublands account for approximately 30% of fires in the region and are particularly prone to fire activity, which threatens this biodiversity-rich ecosystem and nearby human settlements[7]. Like California, variations in precipitation season and amount heavily impact fire activity in South Africa. Drought in this region has been shown to lengthen fire weather seasons, and areas that receive winter rainfall (such as southwest Africa) are more susceptible to fire than those that experience summer rainfall[7,8].

WHAT IS SMOKE TAINT?

The exposure of *Vitis vinifera* vines to smoke from wildfires alters the chemical composition of grapes and the resulting wine, leading to a defect known as "smoke taint". Many different chemicals may be involved in the manifestation of this taint, but the volatile phenols guaiacol and 4-methylguaiacol are the best studied (**Figure 3**). They are the most abundant volatile phenols in smoke and they have a low sensory threshold, making it very likely that they are involved in the sensory expression of smoke taint[9]. In low concentrations, such as those resulting from oak treatments, they impart a pleasant smoky flavour and aroma[10]. However, smoke exposure tends to result in very high concentrations, which can lead to negative sensory characteristics in wine[10].

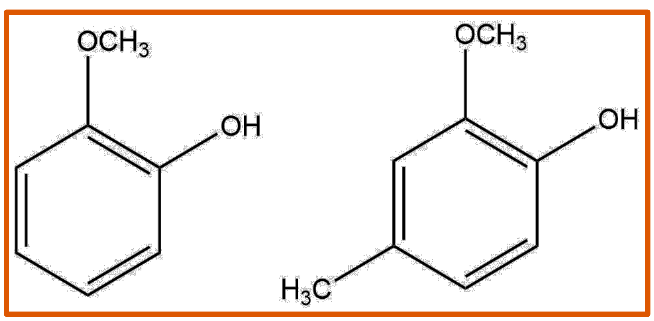

FIGURE 3: VITICULTURE VOLATILES The chemical structures of the volatile phenols guaiacol (left) and 4-methylguaiacol (right), which are common in smoke-tainted wine (created in ChemDraw). Phenols are organic compounds with a hydroxyl (OH) group attached to a benzene ring. Since these phenols are highly aromatic, they earn the moniker "volatile".

TABLE 1: IN POUR TASTE Characteristic flavours and aromas associated with smoke-tainted wine, and the chemicals responsible[9,11-13]. Asterisks denote unspecified or unknown chemicals.

Flavour/Aroma Descriptions	Associated Chemicals
Smoky	guaiacol, 4-ethylguaiacol, o-cresol and m-cresol, 4-methylguaiacol, guaiacol glycoconjugates, 4-methylsyringol, higher glycoside concentrations
Ash, Cold Ash	4-methylguaiacol, o-cresol and m-cresol, guaiacol, 4-methylsyringol
Smoked Meat, Smoky Bacon, Smoke Salmon, Salami	*
Toasted	4-methylguaiacol, 4-ethylguaiacol
Burnt Rubber	*
Stable, Horsy	4-ethylphenol
Leather	*
Earthy, Dirty	syringol, guaiacol glycoconjugates
Metallic	*
Woody	*
Phenolic	guaiacol, 4-ethylphenol
Chemical	guaiacol
Medicinal, Band-Aid, Hospital, Disinfectant	syringol, o-cresol, 4-methylsyringol, low glycoside concentrations
Spicy	4-ethylguaiacol
Bitter	*
Drying	syringol, guaiacol glycoconjugates

Other chemicals thought to be involved in smoke taint include 4-ethylguaiacol, 4-ethylphenol, syringol, various cresols, eugenol, furfural, and their glycosylated forms[9,14]. Together, these chemicals create the distinct sensory profile associated with smoke taint – the descriptions range from "smoked meat" to "Band-Aid". Negative sensory attributes and their associated chemicals reported in the literature are listed in **Table 1**. Some attributes, such as "smoky" and "ashy", are more strongly tied to smoke taint, while others, such as "medicinal" and "burnt rubber", are associated but to a lesser extent[12].

The chemicals associated with smoke taint are derived from the burning of vegetation, which breaks down into different smoke compounds depending on its lignin makeup. Lignin is composed of p-hydroxyphenol, guaiacyl, and syringyl lignin units, and the proportions vary based on vegetation type[15]. Grasses contain all three lignin units, hardwood angiosperms contain mainly syringyl and guaiacyl units, and softwood gymnosperms contain only guaiacyl and p-hydroxyphenyl units. Emissions from these three fuel classes result in smoke with different ratios of phenol, guaiacol, syringol, and 4-methylsyringol[15]. Due to the effect of lignin on smoke composition, regional differences in forest structure likely play an important role in the manifestation and severity of smoke taint in local wines.

Time for a Smoke – The Effect of Exposure Timing:
Studies on Merlot vines have found that multiple exposures to smoke have a cumulative effect on smoke taint, and that both sensory properties and guaiacol concentrations vary depending on the timing of smoke exposure[13,16]. Vines seem to have a peak sensitivity to smoke around seven days post-veraison, although the reasons for this are still unclear. Some proposed theories include changes in grape physiology (such as metabolism and cell wall structure) after veraison[13], and guaiacol's limited translocation rate leading to higher expression in grapes at certain times[16].

ACHIEVING GRAPE-NESS: UPTAKE OF VOLATILE PHENOLS

How do these volatile phenols actually enter grapes? There are two main pathways: directly, by passive diffusion through the grape skin; and indirectly, either through stomata in the leaves or uptake via the roots[9]. Free guaiacol is easily translocated across the grapevine through its vascular system, so all of these pathways may operate simultaneously. However, entry through the roots is thought to be the least important contributor to smoke taint, as climatic conditions tend to be dry during forest and bushfires. It remains unclear whether direct passive absorption through the grape skin or active stomatal uptake through the leaves plays a larger role, and the potential effects of vine physiology on these processes are poorly understood[9].

Regardless, when volatile phenols are taken up into grapevines, they are glycosylated (attached to other functional groups) as a detoxification mechanism[9]. The exact location of glycosylation in grapevines, and whether the process can be manipulated by vineyard management both require further study[9]. In their glycoconjugate state, smoke-derived phenols in wine have no sensory properties, until they are hydrolyzed either during fermentation[17] or in the mouth during tasting[18], releasing the free volatile phenols that give smoke taint its distinctive sensory character.

Aging Tastefully – Smoke Taint after Bottling:
Guaiacol and 4-methylguaiacol are known to continue accumulating in wines from smoke-affected grapes for at least three years during bottle storage[19]. Bound forms of these phenols, likely glycoconjugates, act as an aroma reserve for smoke taint in aging wines, which becomes problematic when assessing or predicting the extent and severity of smoke taint.

VARYING VARIETALS: SMOKE TAINT ACROSS CULTIVARS

The effect of smoke taint can also vary across wine varieties. Differences in volatile phenol concentrations in smoke-exposed grapes of various cultivars have been reported in several studies[9]. In general, red wines tend to exhibit a higher intensity of smoke taint than white wines, likely because they involve a longer duration of skin contact during winemaking[9]. In a recent study measuring the expression of smoke taint in specific cultivars, Ristic et al. reported that Cabernet Sauvignon and Pinot Gris varieties exhibited the most intense smoke-related sensory attributes, with strong "smoky", "ashy", "medicinal", and "metallic" flavours and aromas[12]. They also found an associated reduction in the intensity of the wine's "fruit" flavours, especially for Pinot Gris. Merlot and Shiraz varieties displayed smoke-related sensory properties, with prominent "smoky", "earthy", and "ashy" attributes, but these varieties mainly retained their "fruit" aromas and flavours. Chardonnay wines were less influenced by smoke taint, with only slightly elevated "smoky", "ashy", and "burnt rubber" properties after smoke exposure. Sauvignon Blanc was least affected.

However, some of these variations in the sensitivity of different cultivars may reflect phenology at the specific time and conditions of smoke exposure, rather than inherent cultivar differences[9]. Kelly et al. suggested that cultivar has little effect on the accumulation of phenols when smoke exposure events occur at comparable stages of grape development[9]. In another study, Brodison found that the uptake of phenols at different developmental stages varies between cultivars – for example, Cabernet Sauvignon seemed to be more susceptible earlier in its phenological stages, compared to Merlot[9]. Overall, further investigation is required to better understand the differences between cultivars in uptake and distribution of volatile phenols. In future, this may help inform varietal selection for winemakers in smoke-prone regions, and thus help mitigate the risk of smoke taint.

MITIGATION STRATEGIES

Despite the challenges, winemakers are finding new ways to continue thriving through the flames and smoke. Several early detection methods have been developed, such as the use of near-infrared spectroscopy. This method provides an easy way to measure smoke taint compounds without destroying grapes[20]. A new portable technology called the E-nose (**Figure 4**) uses digital sensors to detect odours more effectively than a human nose, and thus may detect smoke taint earlier in the winemaking process[21]. As chemical taints only become detectable by humans days after smoke exposure, early detection technology is highly advantageous[22].

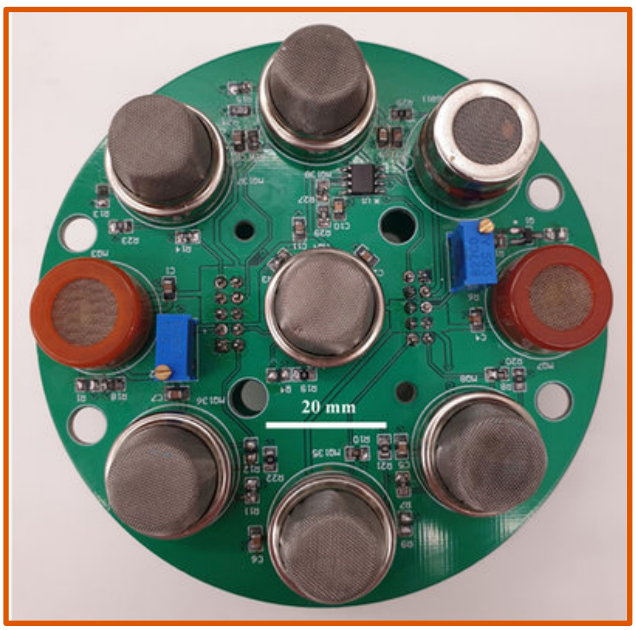

FIGURE 4: E-NOSE KNOWS BEST Portable E-noses can detect smoke taint in wine grapes much earlier than humans are able to[21].

Smoke taint is an overarching problem, altering wine quality throughout the grape-growing, wine-making, and aging stages[23]. Thus, mitigation often involves an integrated approach. One very immediate, proactive technique is the use of agricultural sprays on grapes, which act as an extension to the skin and block smoke uptake[24]. Applying an artificial phospholipid biofilm before smoke exposure, for instance, drops volatile phenol concentrations[24]. A very similar effect is observed from the application of kaolin clay[25]. Chitosan, a glucose polymer sourced from fungi or crustaceans, can decrease uptake of guaiacol and syringol by half when coated on grapes aqueously[26]. Other mitigation measures are done post-harvest; exposure to ozone decreases guaiacol and 4-methylguaiacol concentrations in smoke-tainted grapes and reduces unpleasant features in the resulting wine[27].

Smoke and Tiers – Categorizing Attributes of Wine:
Sensory attributes of wine are often divided into primary, secondary, and tertiary categories. Primary sensory attributes refer to those derived from the fruit itself, whereas secondary sensory attributes are derived from the wine-making process, and tertiary sensory attributes are derived from bottle aging[28]. Focusing on the interactions of these different attributes with respect to smoke taint may provide a solution – yet there exists a "research gap" in this area, according to œnologist Matthew Noestheden[23].

During winemaking, additional steps can be taken to help alleviate smoke taint. Maceration (**Figure 5**), a red wine-making method that can reduce phenols, can be of use to winemakers plagued by wildfires[29]. Similarly, filtration processes such as reverse osmosis[29,30] and nanofiltration[31] can decontaminate smoke-tainted wines. However, reverse osmosis may also remove other wine components[30], including those responsible for desirable aromas and flavours[23]. Chemical additives can also be of use. One example includes activated carbons, which have

FIGURE 5: MACERATE GOOD TIMES Wine grapes undergoing maceration, a method of winemaking that limits overall concentration of phenols in wine[32].

been effectively used to remove fungal taints from wine. Some commercially available activated carbon products are already showing promise as phenolic glycoside removers[33].

Swing and a Mist – Failed Mitigation Techniques:

Several attempted strategies for reducing smoke taint in wine have proven ineffective. These failures include:

- Washing smoke-exposed grapes in water or milk[22]
- Misting smoke-exposed grapes with water using in-canopy sprinklers[22]
- Applying a polymer concentrate (marketed commercially as Envy) to the skins of smoke-exposed grapes[25]
- Applying a fungicidal spray derived from tea tree oil to the skins of smoke-exposed grapes (this technique actually resulted in an increased uptake of volatile phenols, worsening the smoke taint)[24]

Unfortunately, none of the current methods can perfectly remove smoke taint from wines. As a result, some winemakers may prefer methods to mask the smoke taint, as they can provide other sensory benefits as well. Adding oak chips or oak extract can enhance a wine's flavour and thus disguise its smoke taint[23,29,30]. Tannin additives, derived from plant materials, are often used as flavour boosters[29]. Recently, it has been proven that they can sequester phenols, essentially "neutralizing" and removing smoke aromas from tainted wines[23].

IMPLICATIONS FOR THE WINE INDUSTRY

Whether at the primary, secondary, or tertiary level, the urgency of mitigation methods cannot be overstated. As with other aspects of climate change, the increasing number and severity of wildfires will continue to devastate vineyards if not addressed – but what specific implications will this have for the wine industry?

MONEY TO BURN: ECONOMIC IMPACTS

Wine is a large source of revenue, as California wine generated approximately $43.6 billion USD in 2019[34]. Due to its economic influence, a reduction in grape quality through smoke exposure may have dire financial consequences. This trend has been observed in Australia, a region with a significant wildfire and viticultural presence. Three Australian bushfires, in 2003, 2007, and 2009, resulted in losses within the wine industry of $23 million, $150 million, and $330 million AUD, respectively[35]. While studying Australian wildfires may lend insight, the full extent of this issue in other regions is unknown.

RACK AND RUIN: WINE TOURISM

Wine tourism is an aspect of viticulture which is often forgotten, despite its importance in generating revenue and advertising wines. Wine tourism is responsible for generating $7.2 billion USD annually in California alone[36]. This industry, similar to the overall wine industry, has been negatively influenced by wildfires and smoke-tainted wines. However, due to the multifaceted nature of this industry, there will be a variety of consequences. Tourists are less likely to travel to vineyards affected by wildfires[37], which could lead to an overall decrease in profits compared to previous years. Additionally, a reduction in tourism can have a larger impact beyond fewer tourists showing up to purchase wines. The reputation of a vineyard is often influenced by wine connoisseurs who partake in wine tours of different regions to identify good wines and then spread this knowledge through conversations or social media[36]. Wildfire-affected vineyards would be unavailable for these tours and would not be able to provide wines at their usual quality. As a result, the reputation of these vineyards will likely worsen. The rise of social media adds yet another layer into this problem, as smoke-tainted wines and wildfires can negatively impact a vineyard's online presence through negative reviews or a lack of online support. This loss of reputation and decreased presence could lead to even lower global wine sales in the modern, interconnected world.

CONCLUSION

Under the threat of worsening fire seasons, the wine industry and many of its associated industries must brave the smoke and flames. Multiple strategies and techniques have been developed in order to mitigate smoke taint in wines, although many are still under investigation, and interventions that may be required for more recent fires are still unclear. As changes to the human and natural worlds alter fire patterns, winemakers must assess their individual risk of smoke exposure and consider appropriate mitigation strategies. Despite the challenges posed by increasing fires, many of their potential impacts on wine remain to be seen – and as much as this uncertainty is frightening, it may also provide a unique opportunity for the wine industry to evolve.

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MORE TO EXPLORE

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Photograph courtesy of Josh Edelson / AFP via Getty Images. US-California-Fire 24/10/19 – Wine Spectator News [Internet]. [cited 2020 Nov 11]. Available from: https://www.winespectator.com/articles/could-vintners-protect-grapes-from-wildfire-smoke.

Climate and Wine:

How Climate Change Will Affect Winemaking in Queensland.

Michael Celejewski, Emma Luymes, Nicholas Skaljin, Jonathan Spence and Dominic Wood

Over the remainder of the 21st century, climate projections are grim. Temperatures are projected to increase, and weather patterns are projected to become more extreme. With these projections come a plethora of issues, affecting agriculture, and more specifically, viticulture. Viticulture around the world will be altered, and the winemaking landscape is destined to be changed, with many regions facing uphill battles to keep their lucrative industry alive. One of these affected regions is the Province of Queensland in Australia.

Climate change is expected to severely impact Queensland, resulting in skyrocketing temperatures, and increasing the severity of drought in the dry season while also increasing the likelihood of large storms in the wet season. As such, these climatic conditions will likely have a vast impact on the terroir of Queensland, being detrimental to microbiota, soil conditions, and water availability.

Introduction

Terroir, the collection of natural elements that influence grapevine growth, is all-encompassing, and to understand terroir, one must consider all aspects of viticulture, from the meticulous growth of grapevines to regional characteristics that bring out the best in the most ubiquitous dinnertime beverage, wine [1]. However, it is inevitable that viticulture will change with climate. Changes in temperature, precipitation and erosion rates will alter terroir across the world, but each region will experience this process differently. Some notable winemaking regions that are predicted to experience a change in terroir lie in Queensland, Australia. In order to understand the changes in terroir for a given region, it is important to consider the scale of climate change that Queensland may experience in the future. As such, this report will investigate the implications of the information gathered from a Queensland regional climate model. These results will aim to shed light on how terroir as we know it may be affected towards the turn of the century.

Climate Change Modelling for Australian Viticulture

There is no "one-size-fits-all" method of modelling climate change. Not all aspects of climate can be modelled [2], and each climate model relies on assumptions, such as the representative concentration pathways (RCPs), which are predicted scenarios for future greenhouse gas levels in the atmosphere [3]. In the case of Australian viticulture, the most studied regions are Victoria, Queensland and Tasmania [4]. Queensland, in particular, is predicted to have high temperature increases over the course of the century [5]. The Queensland government's regional climate model was created through regional downscaling with the fifth phase of the Coupled Model Intercomparison Project (CMIP5) as the underlying global climate modelling experiments [6]. CMIP5 modelling involves long-term simulations that can span across centuries, but is also capable of short-term predictions [7]. A global climate model input was used to create a regional climate model output, and this is known as a dynamical downscaling approach [6].

Temperature changes, precipitation and other climate variables can be predicted based on various RCPs [8]. Carbon dioxide concentrations are assumed, even though they are not necessarily predictable because this factor relies on many socioeconomic variables, such as the change in land use or demographic shifts [8]. In addition, the impact of socioeconomic factors is challenging to quantify [8]. In the case of Queensland, the main RCPs that account for specific greenhouse gas concentration scenarios are RCP8.5 and RCP4.5. RCP8.5 reflects the worst possible scenario, in which there is little curbing of emissions, resulting in a rapid rise of carbon dioxide concentrations over the course of the century, whereas RCP4.5 involves a steady increase in carbon dioxide concentrations that stabilizes around 2060 [5]. There are several other RCP scenarios, each with their own unique relationship to gas concentration trends (see Figure 1).

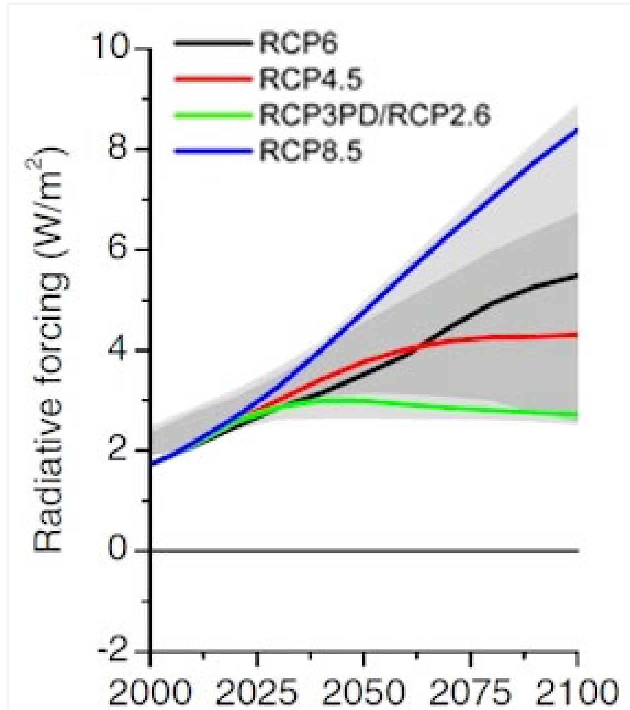


Figure 1: A visual representation of Queensland's most prominent RCPs, in which radiative forcing (y-axis) acts as a proxy for relative atmospheric greenhouse gas concentration over time (x-axis). Additional scenarios in the graph include RCP3PD, which represents drastic intervention, leading to a reduction in greenhouse gas concentrations, and RCP6, which is a gradual stabilization scenario leading to plateauing radiative forcing by the turn of the century [5].

Based on RCP8.5, changes in annual precipitation by 2090 range from -0.40 to 0.56 mm/day, whereas RCP4.5 predicts a change between -0.49 to 0.32 mm/day (see Figure 2) [5]. Based on RCP8.5, changes in mean annual temperature by 2090 are approximately 2.6 to 5.7 °C, whereas the RCP4.5 predicts an increase from approximately 1.1 to 3.0 °C (see Figure 3) [5]. It is anticipated that these changes, among others, will affect soil composition, microbial growth and the drought prevalence of Queensland in the future.

Soil Erosion and Degradation

Climate change and common agricultural practices such as tilling, preparing the soil by mechanical digging or overturning, are contributing to widespread soil erosion and degradation that is detrimental to the global economy and environment in the present and future. As soils lose nutrients, organic matter, and water holding capacity with erosion, the biodiversity within a soil is lost, and the components of terroir are dismantled [9]. Viticulture is often at an increased risk, since its typical location in steeply sloping hillside vineyards, is prone to serious erosion. As vineyards continue to choose to maintain bare soils, erosion intensification will likely carry on as the surface is exposed to greater erosion practices [9,10]. Furthermore, controlled nutrient availability to vines is paramount to a viticulture plan. This control becomes increasingly challenging as a soil's nutrient quality and structure are increasingly degraded and require more intervention. The cause of this erosion and its secondary effects is primarily water, as percussive rainfall and subsequent overland flow dislodge and carry particles. Climate modelling shows an increasingly vigorous hydrologic cycle which will impact dryer regions with infrequent, larger rainfalls during Queensland's wet season (Figure 2) [11,12]. Soil sustainability is directly addressed in the UN's Sustainable Development Goals and is increasingly acknowledged in the wine industry as the future maintenance of healthy soil is not guaranteed [13].

The effects of soil erosion and degradation are cause for concern in all global wine regions. European vineyards, for instance, represent the most devastating agricultural land use in the continent[14]. In Australian agriculture, the effects of soil erosion have persisted at large scales since the middle of the 20th century [15]. Sustainable soil management will play a large role in the future of the wine industry as well as in the health of ecosystems affected by secondary effects of current practices. The study of climate change implications on Australian viticulture lends applications to viticulture and agriculture in regions that will experience changes that are similar to Australia's in the coming decades.

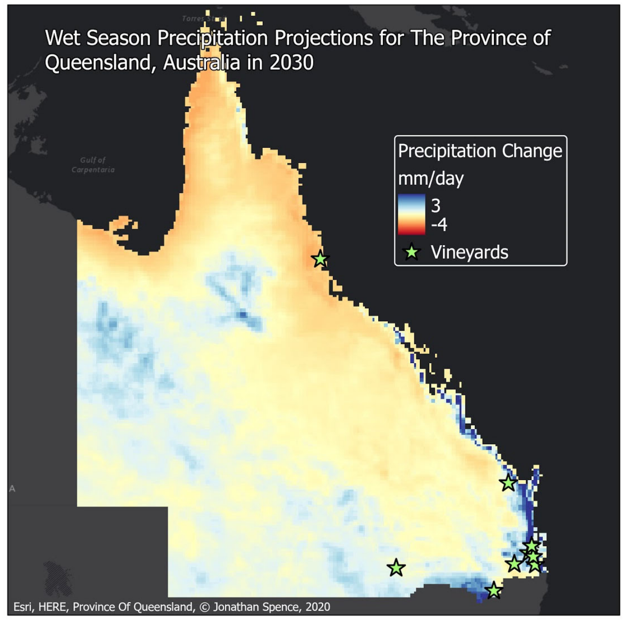
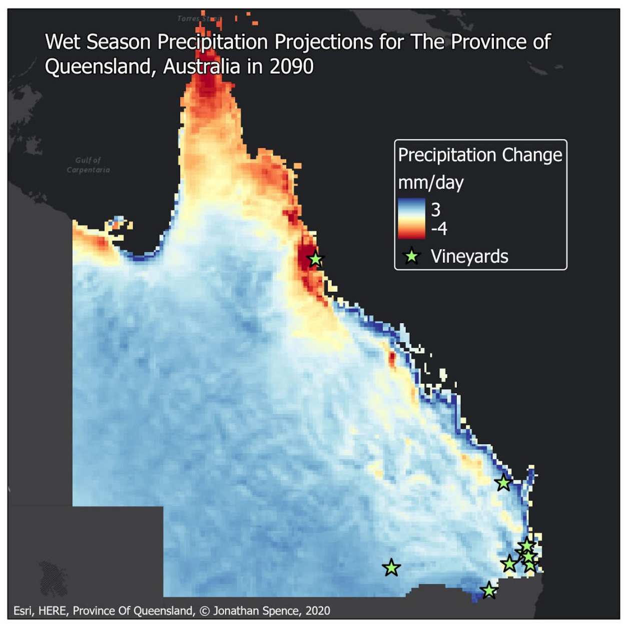


Figure 2: Precipitation change projections for 2030 (above) and 2090 (below) under the RCP8.5 scenario [5,16].



Microbiota

One of the factors that affects terroir and the regional distinctiveness of a wine is the community of microorganisms present in a vineyard, known as a vineyard's microbiota. The fungi and bacteria in a region have an effect on soil composition and plant growth, which subsequently affects wine quality and flavour [17]. Microorganisms can positively impact the growing environment by improving the soil's nutrient content, or they can act as pests and harm plant growth. The microorganisms present depend on the climate of the region, including the temperature, sunlight and moisture availability [18].

Microorganisms that affect grapevine health and growth can originate from the vineyard soil or be transported to the vineyard through the air, water, or animal vectors [18]. Once at the vineyard, microorganisms such as nitrogen fixing bacteria or phosphate mobilizing bacteria can alter chemical properties of the soil. This alters soil nutrient content, adding nitrogen and phosphate, which can increase wine quality [19]. Microorganisms can also directly impact the plant roots, vines, and berries. Root rot, powdery mildew, and a variety of other bacterial pathogens will grow directly on the plant, impeding plant growth [18]. Microorganisms can also affect wine quality at the fermentation stage. *Saccharomyces cerevisiae* is the yeast used to ferment sugar in wine. This process produces ethanol and carbon dioxide in addition to important volatile metabolites that enhance the flavour profile. Different strains of this yeast contribute different flavours to the finished wine [17]. For example, metabolites like ethyl isobutyrate and ethyl-2-methyl butanoate add sweet apple flavours, while ethyl butanoate adds a peach flavour. The release of these chemicals depends on the genetic makeup of the yeast strain. The strain of yeast present in a region results from a change in allele frequencies over time in response to its environment. Because the strain of yeast is unique to a location, it adds a sense of regionality to the wine [20].

In general, the microbiota present in a vineyard depends on the surrounding location and environmental conditions. Although the microbiota in Queensland vineyards can survive under the current climatic conditions, this may not be the case in the next few decades. As a region's climate changes, microbiota present in previous years may no longer be able to survive in those vineyards and will be replaced by organisms that are better suited to the new climate. This change in microbiota will likely alter vine growth and/or fermentation processes, ultimately leading to a change in wine quality and regionality [20]. Limited but increasing evidence suggests that environmental heterogeneity conditions microbial biogeography in wine production on different spatial scales. Local climatic conditions significantly correlate with microbial compositions. A study conducted by Bramley et al. investigated the effects of rotundone concentration in Australian cool climate 'Peppery' Shiraz grapes related to vineyard soil microbiome composition [21]. Typically found in the soil, rotundone is a part of a class of terpenes, a large and diverse class of organic compounds that are produced by a variety of plants, particularly conifers, and by some insects. Additionally, rotundone is known to impact the peppery aroma of a wine [22]. This study found that different zones within the same vineyard are associated with different propensities for grape berry rotundone concentration. The soils with high amounts of rotundone exhibited higher diversity of bacteria but lower diversity of fungi compared to soils with low rotundone concentrations [21]. As the temperature rises and climate changes, the amounts and variety of organic compounds (e.g., rotundone) as well as microbiota will be significantly impacted. More specifically, rotundone is typically more abundant in cooler temperatures, meaning the rise in temperature will likely decrease the concentration of rotundone in the soil. This will ultimately decrease the diversity of bacteria, while increasing the diversity of fungi. This change will ultimately impact the regionality and terroir of the different wine regions in Queensland.

A study conducted by Bååth et al. investigated the effects of temperature on fungal and bacterial growth rates. The results indicated that fungal and bacterial growth rates had optimum temperatures around 25–30 °C, whereas lower growth rates were found at higher temperatures [22]. This decrease was more drastic for fungi compared to bacteria, resulting in an increase in the ratio of bacterial to fungal growth rate at higher temperatures. A tendency towards the opposite effect was observed at low temperatures, indicating that fungi were more adapted to low-temperature conditions than bacteria [23]. Currently, the mean annual temperature in Queensland is around 29 °C. Climate change models predict that there will be an increase in temperature that is approximately 1.1 °C and 4.4 °C respectively, by 2030 and 2090 (Figure 3)[5]. This indicates that the temperatures will be well above the optimal growth rate temperature for bacteria and fungi. Ultimately, this will result in a decrease of bacterial and fungal diversity. However, it is important to note that there appears to be some contradictions in the current literature. For example, as mentioned earlier, high rotundone soil concentrations are more favourable to fungi, but rotundone is more abundant in cooler temperatures. As seen in the GIS predictions, the temperature will rise significantly, which is more detrimental to fungal growth. Therefore, there is still some uncertainty on how temperature rise will affect bacterial and fungal diversities as a whole. Nevertheless, microorganisms play a vital role in grape vine health and growth. The variety and amount of microbiota will be impacted by this increase in temperature and thus will inevitably affect wine quality, regionality and terroir in the Queensland area of Australia, but to what extent is still fairly uncertain.

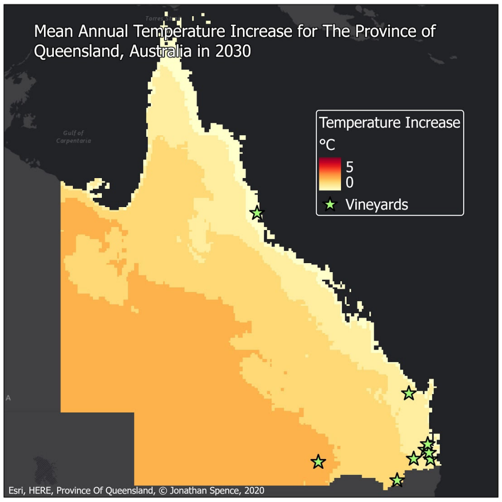
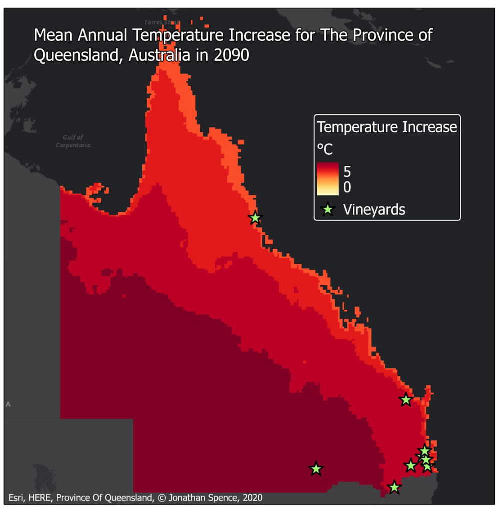


Figure 3: Mean annual temperature increase for 2030 (above) and 2090 (below) under the RCP8.5 scenario [5,16].



Hydrology

Another factor that will be analyzed in our study of Australian viticulture is water availability. Winemaking is an incredibly water-heavy process. In fact, to produce one bottle of wine, an average of 632.2 litres of water is required. More importantly, on a world-wide scale, 98.3% of this water is green-water, which means that it is fresh, drinkable water [24]. This is a huge issue for drought-prone viticulture regions such as Australia, since water rationing is essential, especially in summer months. As of August 1st, 2020, 67.4% of Queensland's land area was located within a drought-declared region [25]. Many wineries fall within these regions, and the drought region is only expected to grow. In fact, by 2090, Queensland's daily dry season precipitation is expected to fall 25%, in addition to evaporation rates increasing by 29% [5]. This will place further stress on the viticulture industry, thus requiring significant adaptations to be made from both a water acquisition and conservation standpoint.

By using ArcGIS to analyze data from the Queensland government on precipitation projections and evaporation rate projections, projections for locations at risk of drought can be made. Within Figure 4, areas in red are at the highest risk for worsening drought conditions, while those in yellow are at a moderate risk, and those in blue are at a low risk. Comparing these areas to the locations of Queensland's vineyards, worrisome trends can be seen. In the year 2030, only two of these nine vineyards will be in areas of moderate risk of worsening drought. However, by 2090, six of these nine vineyards will be in areas that are at a moderate risk of worsening drought, and one vineyard will even be located in an area at high risk. This has vast implications both economically and environmentally for Queensland, as a large increase in water resource diversion will be required if the province hopes to keep this fruitful industry.

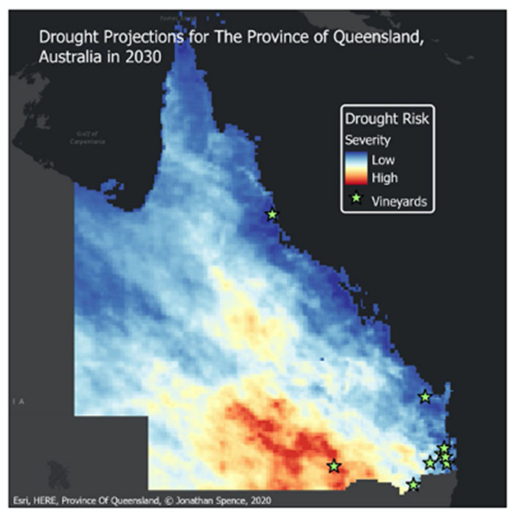
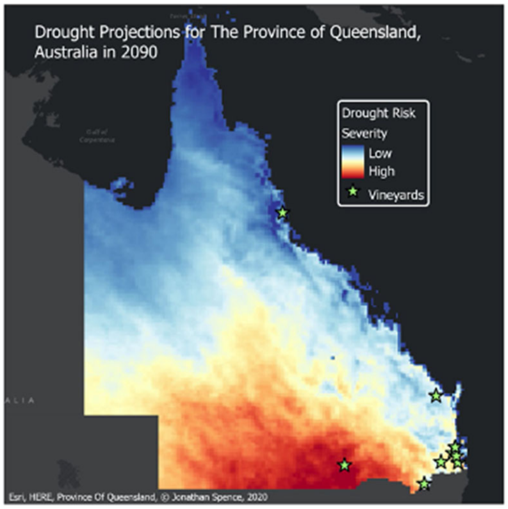


Figure 4: Drought projections for 2030 (above) and 2090 (below) under the RCP8.5 scenario [5,16].



Mitigation Strategies

While these climate change scenarios pose a bleak outlook for the future of Australian and global viticulture, a transition from long term detrimental soil management practices towards sustainable ones would improve the outputs of the wine industry. Cover crops simultaneously solve various problems vineyards face by simulating natural conditions and capitalizing on existing ecological interactions [8]. These alternative crops grow in between vines, protecting the soil surface, prevent erosion and weed growth, and support biodiversity and integrated pest management and achieve the same or better results as with chemical or physical interventions [27]. In vineyards, cover crops have proven to reduce soil and organic matter loss as a result of water erosion [8]. In addition to soil erosion mitigation techniques, water conservation must also be considered. Techniques such as grey-water utilization, meaning the reuse of non-contominated residential water, and water rationing guidelines should be implemented so that there is enough water for both human needs and agriculture.

Covering up with Clover: A well-studied cover crop and relatively ubiquitous genus, *Trifolium* is often an ideal candidate for cover cropping programs [27]. Depending on desired outcomes, precipitation, and planting schemes, several cover crop selection tools exist to give vignerons accessible information about cover crops.

Conclusions

It seems that only time may tell what changes will come for Australian viticulture; however, with many years of climate change research and modelling, increasingly accurate predictions can be made about future conditions in Queensland. Alterations in soil, microbial composition and hydrology will cause compounding changes to the composition of wine that is traditional to the region. It is only with extensive planning for mitigation practices that the world may preserve the qualities of wine that are valued in each given region. Tackling the effects of climate change for the purpose of viticulture cannot be limited to one aspect of terroir, as all aspects must be sustained for wine to retain its character. Sustaining these characteristics will allow humans to continue their beloved tradition of celebrating with friends and family by cracking open a distinct regional wine for centuries to come.

MORE TO EXPLORE

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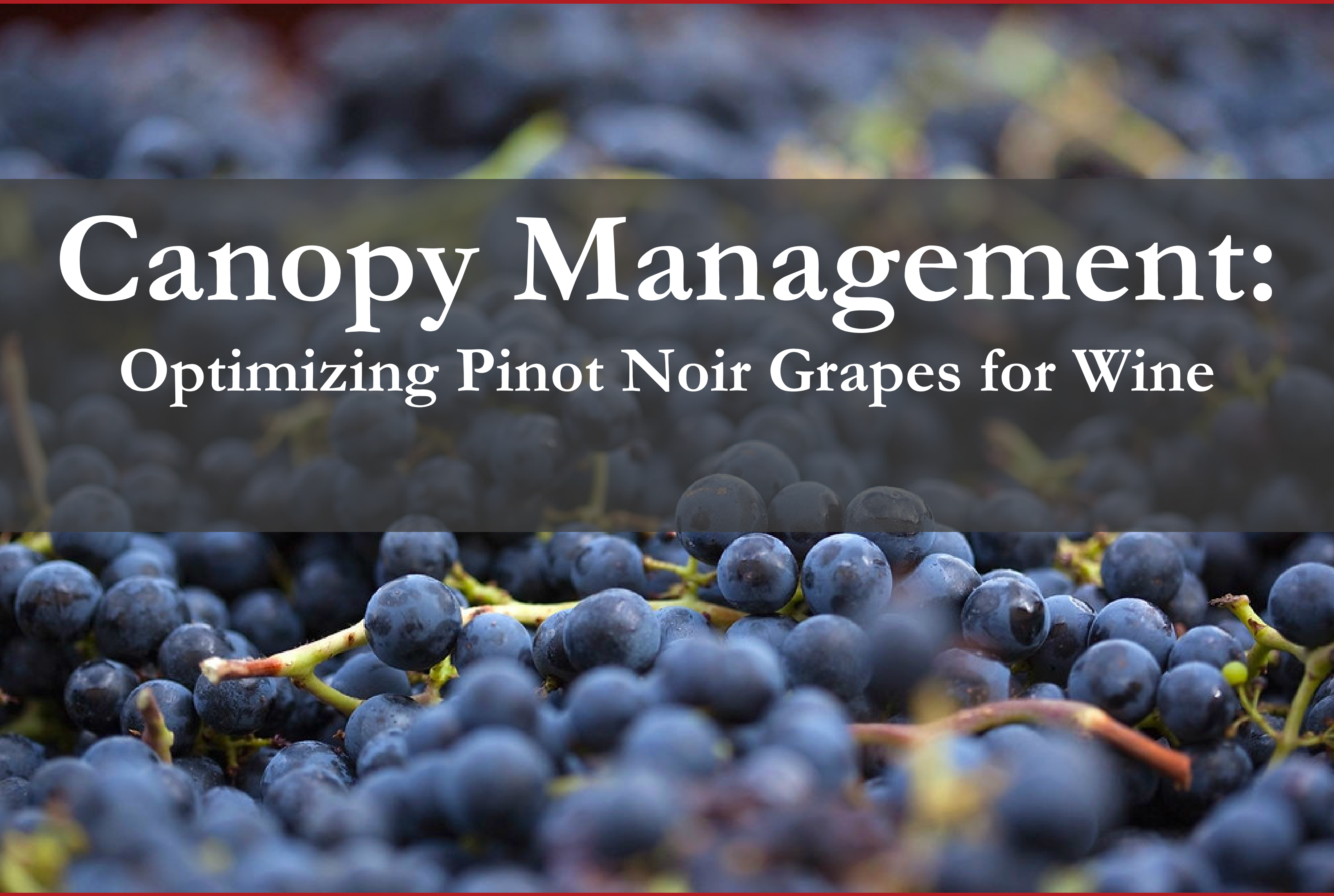
Canopy Management:

Optimizing Pinot Noir Grapes for Wine



Shannon Buck, Maia Moore, Bronwyn Riddoch, Mya Sharma, Julia Singer

Canopy management is an important component of viticulture. Pruning techniques, training systems, microclimate manipulation, and pruning timing must be considered to optimize grape and wine quality to suit the climate, varietal, and vigneron preference.

A range of canopy management practices are explored to improve the quality of Pinot noir grapes. Based on the literature, we recommend vignerons manually cane prune their vines and employ a vertical training system to improve grape quality. We propose vignerons perform basal defoliation to increase sunlight exposure to benefit wine aroma, flavour, and colour. Vignerons should also consider double pruning their grapevines to mitigate the effects of climate change and maintain yields. Although these practices can improve Pinot noir grape and wine quality, individual management strategies should be designed by the vigneron to consider localized climate and growing conditions, as well as vintner and market preference.

INTRODUCTION

Canopy management of vineyards is a crucial component of viticulture. Different grape varieties require tailored management practices in order to create the ideal wine. Canopy management includes: training systems to support vines, pruning techniques, pruning to alter microclimate, and pruning timing. The optimal combination of these practices is essential for producing the highest quality grapes, which is directly translated into wine quality.

When considering the canopy management practices to optimize grape quality, it is necessary to consider the cultivar grown. Here, we propose an optimal canopy management program for Pinot noir grapes. Pinot noir, a varietal of the *Vitis vinifera* grape, originates from Burgundy, France. It is now grown worldwide in a range of climates[1]. For instance, Pinot noir accounts for 56% of the vineyard acreage in Oregon[1]. The fruit of this variety is commonly used in Pinot noir wines, which have a characteristic dark red colour, and in some sparkling white wines[1]. Pinot noir is distinguished by low crop yields and high market prices[1], which are important factors to consider when selecting a pruning technique. It is therefore of great importance for vignerons to optimize crop yield and grape quality to maximize profits.

TRAINING SYSTEMS

Training grapevines is one of the most important aspects of vineyard management. Training systems manipulate canes and shoots, while supporting the grapevines[2]. The manipulation also determines the direction of growth, resulting in either vertical or horizontal planes. Most of the time, exterior supports are needed, such as a trellis or a stake, but the setup of the support depends on the training system in place[2,3]. These supports provide ease of equipment movement within the vineyard and benefits plant health[2].

Training systems can be classified into four major categories: head/cane, cordon/cane, head/spur, and cordon/spur, with each category having specific methods for vine manipulation[2] (Figure 1). Head or cordon indicates how the plant has been trained to grow and where new growth occurs[2]. Cane and spur refer to the pruning systems, which will be discussed in the next section. When a head trained system is in place, the cane or spur growth occurs at the top of a short trunk[2]. The structure of a grapevine can be seen in Figure 2. When a cordon system is used, the canes and spurs are formed off of the cordon[2].

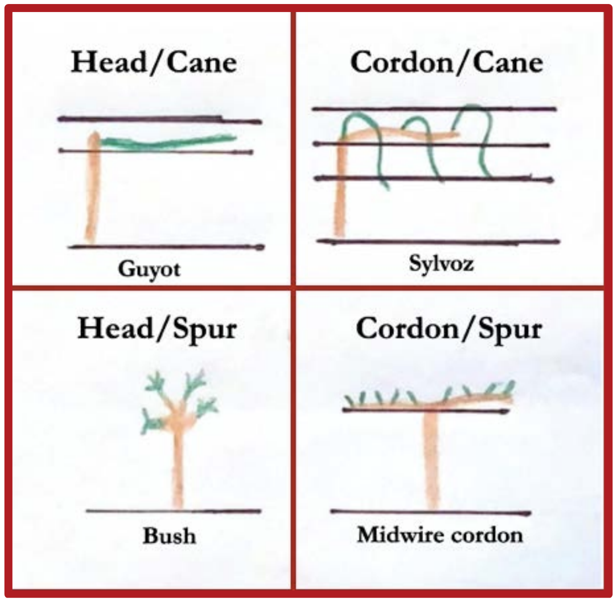


FIGURE 1: THE FOUR COMMON CATEGORIES OF TRAINING SYSTEMS. The four main classification categories are visually represented, with an individual training system included to illustrate the differences. Brown, green, and black lines represent old growth, new growth, and wires, respectively. Adapted by authors[4].

Common systems used in cool-climate North American wine regions are the Six-cane Kniffen, Umbrella Kniffen, Scott Henry, Guyot, Pendelbogen, and Lyre, which are illustrated in Figure 3[6]. Most of these training systems fall into the vertical head/cane category[6,7]. Many of these systems reduce grapevine winter injury rates by shaping the vines to allow snow accumulation, insulating the vines from extensive freezing[7]. This causes training systems to be an important consideration in cool climates.

Factors to Consider in Viticulture: Vignerons must consider grape cultivar, growing practices used in the vineyard, disease susceptibility, and resource availability when choosing a training system[4].

Focusing on Pinot noir grapes, a study in 1994 by Reynolds et al. showed that when utilizing a Scott-Henry training system, a cane pruned vertical training system, the vines can maintain a high yield and there is little compromise to the fruit composition[8]. An additional benefit of the vertical system is the reduced leaf and fruit shading[8]. Reynolds et al. hypothesized these benefits contribute to improved fruit and juice composition, as well as wine colour. On the other hand, contradicting research was published in 2002 by Peterlunger et al. which concluded the impact of the training system was minimal on the juice and fruit quality, and

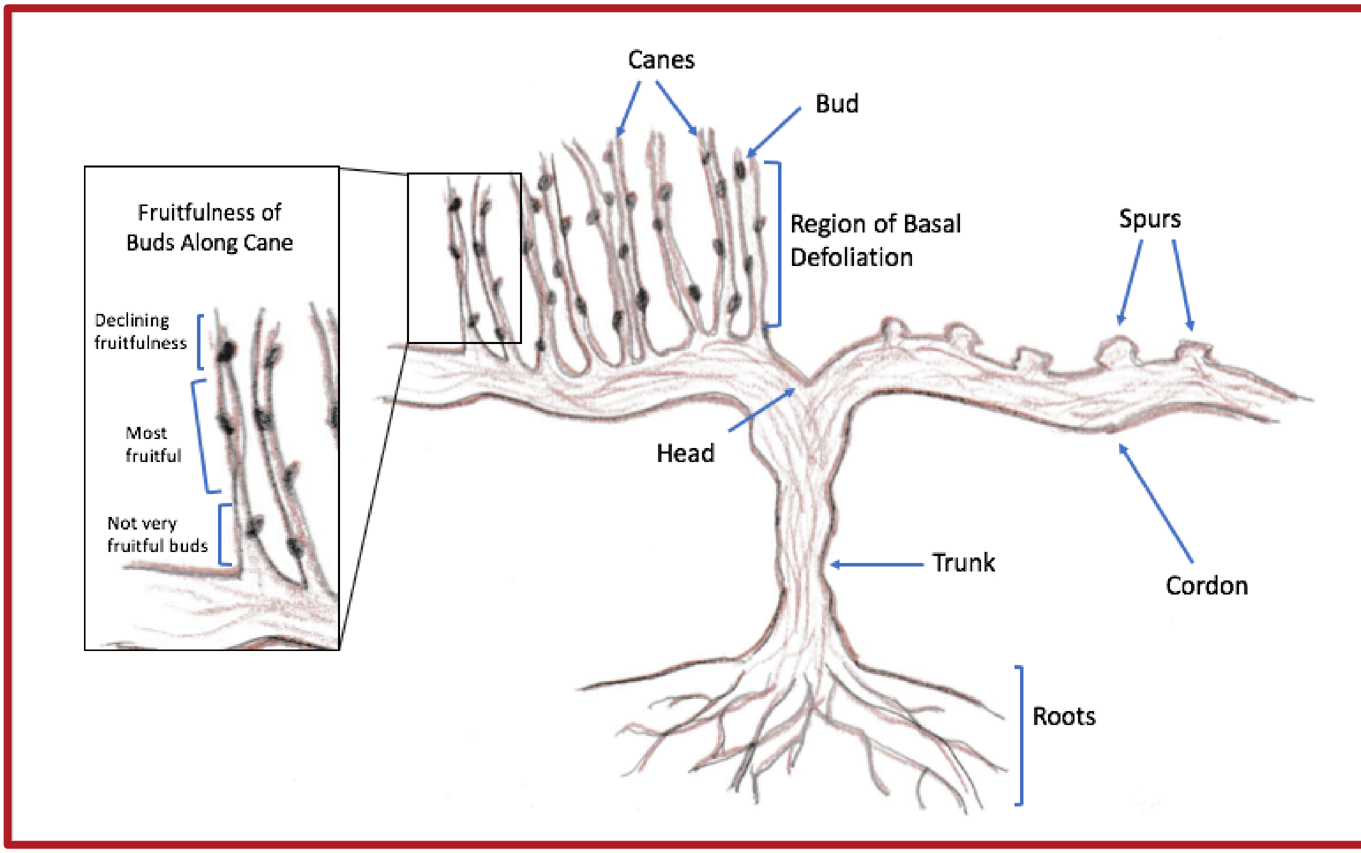


FIGURE 2: THE GRAPEVINE. Anatomy of a grapevine and the different regions of fruitfulness on canes, with the middle of the vine being the most fruitful region. Adapted by authors[4,5].

the best training system to use in an individualized decision[9]. However, the study done by Peterlunger et al. showed that the overall best performers were the horizontal spurred cordon and vertical spurred cordon, with a poor performance from a simple Guyot system[9].

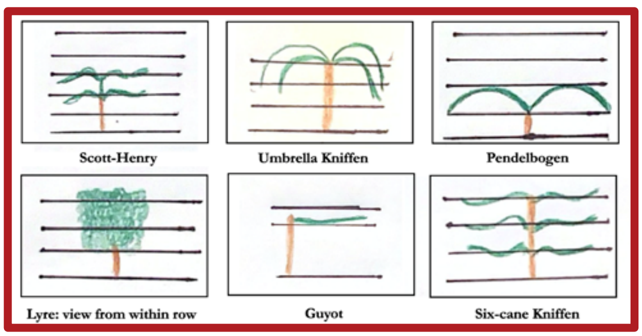


FIGURE 3: COOL CLIMATE TRAINING SYSTEMS. Illustrated are the six most common training systems for cool climates in North America. All of these systems are of a head/cane system classification, with all growth in the vertical plane, but the Lyre system. Brown, green, and black lines represent old growth, new growth, and wires, respectively. Adapted by authors[6].

There are many training systems that can be used in grapevine management, and they are important for vignerons to consider. The literature suggests the most optimal systems for Pinot noir grapes are vertical spurred cordon and horizontal spurred cordon.

PRUNING TECHNIQUES

Another important canopy management technique is pruning, the strategic cutting and removal of vines to leave only a certain number of buds or canes[10]. Vines are usually pruned in the winter when they are dormant and leaf-free[10]. Two common techniques are cane pruning and spur pruning. In cane pruning, most new canes from the past year and all older canes are removed, leaving a subset of healthy canes for the following year whose buds will produce shoots[10]. In spur pruning, new canes that have grown from permanent cordons are removed, and shoots are forced to grow from the basal buds, also known as spurs[11]. Pruning is typically done by hand or by a machine. Both methods have their inherent strengths and weaknesses, but vignerons may prefer one over the other depending on many factors, including grape varietal and climate. Vines are traditionally pruned by hand, which is often the most expensive and labour-intensive task in the vineyard[10].

Mechanical pruning options, have been developed in recent years, and are widely used (Figure 4). Advanced technology has led to even more precise, innovative machines. Designing an automated pruning machine is challenging: a model of the vine structure is necessary to decide where cuts will be made, but spatial algorithms have difficulty modelling the tangled network of overlapping canes[10]. Botterill et al. have invented a computer vision system for reconstructing high-level three-dimensional (3D) models of the vine and trellis' structure from two-dimensional (2D) images[10]. This machine is a vine-pruning robot mounted on a mobile platform that straddles individual vine rows, which are imaged by three cameras[10]. As the robot moves along the row, the 2D positions of canes from each image are reconstructed in 3D, and once the entire model is complete, an artificial intelligence algorithm decides which canes to prune[10]. The entire process occurs simultaneously, with the robot only stopping to make cuts, and the trajectory estimate is highly accurate[10].

FIGURE 4: MECHANICAL PRUNING. A machine pruning grapevines. The operator decides where to make the cuts and how frequently. Note how the machine functions "over-the-vine" and is capable of fitting through the narrow spaces between rows[10].

Research has been conducted on the optimal pruning techniques for Pinot noir vines. Pinot noir grapes are thin-skinned and susceptible to sunburn, disease, and temperature increases[12]. Hand or mechanical pruning can expose clusters to sunlight and higher temperatures during the growing season, so vignerons should prune judiciously[12]. Although lighter pruning generally increases yield, it may be correlated to negative effects on fruit quality, such as lower total soluble solids (TSS), modified pH, and increased titratable acidity (TA)[13].

TSS and TA: TSS is the measure of the amount of sugar in the wine and TA is the measure of total acid. The ratio of TSS to TA is a key consideration vignerons make when deciding when to harvest grapes[13].

The wine industry generally accepts that Pinot noir produces two bunches per bud, which is a low yield compared to other varietals[13]. In Oregon, Pinot noir vignerons prefer head training and cane pruning over cordon training and spur pruning to maintain consistent yields[14]. As labour availability decreases and production costs increase, vignerons are interested in mechanizing and transitioning to spur pruning[14]. However, there is still hesitation to adopt spur pruning, since many vignerons believe Pinot noir has unfruitful basal buds, which would result in reduced and inconsistent yields[14].

Both hand and mechanical pruning can be labour-intensive, costly, and environmentally damaging. Once vines have been pruned, they still require maintenance through defoliation. Animal pruning is a novel alternative used to reduce fuel usage, energy consumption, and greenhouse gas emissions[15]. Using sheep for leaf plucking is becoming increasingly common, since they readily consume grapevine leaves, but not the berries[16]. Fuel consumption from one-time animal transportation is the sole associated cost[15]. Sheep should pluck between fruit set—when flowers form immature grapes—and ripening onset, but need to be monitored so they do not over-pluck[15]. Vignerons have observed that sheep are gentler than people or machines when plucking leaves, and it appears that sheep tend to remove more internal leaves, opening the canopy to improve air flow and lessen disease pressure[16].

Pruning is a canopy management technique that can be accomplished by hand, machine, or animals. Although machine pruning is highly efficient, research suggests manual cane pruning pruduces higher quality Pinot noir grapes.

PRUNING USED TO ALTER MICROCLIMATES

The microclimates around grape clusters can be modified through pruning techniques to change the quality of the grapes and resulting wines produced. Basal defoliation, the removal of leaves and sometimes shoots in the cluster zone, is one of the most common viticultural practices used to modify microclimates[17,18]. This causes increased sunlight exposure, temperature, and air circulation in the cluster zone[17]. Increased

Cluster Zone: The cluster zone, which is where basal defoliation occurs, is the area surrounding the grape bunches[20].

air flow caused by basal defoliation also decreases fungal infection rates, which can reduce loss in yield[17–19]. The practice of basal defoliation is more commonly used in cool, high-humidity climates due to the increased temperature and air circulation around the clusters, combatting the less optimal growing conditions[17].

Traditionally, leaf removal is performed after fruit set until ripening onset; however, recent experiments have studied the effects of leaf removal before flowering[19]. Early leaf removal decreases fruit set in addition to removing leaf density around the fruit zone[19]. This increases cluster looseness and therefore tolerance to fungal infection more than traditional basal defoliation[19]. Thus, early leaf removal is an option for reducing yield in highly productive vineyards where heavy clusters are more susceptible to fungal infection[19]. Traditional basal defoliation performed at or near ripening onset in warmer climates may also cause the grapes to sunburn due to a sudden increase in sunlight exposure, damaging grape quality and anthocyanin levels[17,19]. Early leaf removal can mitigate the risk of sunburn as some cluster leaf cover will reform before the end of the season, when the chance of sunburn is higher[19].

The effects of basal defoliation on Pinot noir have been studied, with results generally in favour of defoliation when grape and wine quality are considered. Defoliation of the cluster zone by 50% or 100% does not significantly impact the shoot numbers, cluster numbers per vine, vine leaf area, or yield[20]. Berry maturity—quantified by levels of TSS, pH, and TA—was also found to be insignificantly impacted when compared to 0% leaf removal[20,21]. Anthocyanins, which provide grape pigmentation, were found to be significantly increased due to higher sunlight exposure caused by defoliation[20,21]. Cluster zone defoliation was also found to enhance colour stability and intensity in wine by increasing the concentrations of two quercetin glycoside compounds[20]. Additionally, β-damascenone, linalool, geraniol[20], and certain esters[21], which are beneficial to wine aroma and flavour, were increased.

Basal defoliation is a microclimate-modulating technique that may be used to improve the quality of Pinot noir wines without negatively impacting quantity. This technique has positive effects on vine health and increases favourable compounds associated with the colour, aroma, and flavour of the wine[20,21]. In cooler, more humid climates, traditional basal defoliation of Pinot noir vines at 100% leaf removal in the cluster zone is recommended by literature[20,21]. More moderate climates that do not require the same level of intervention to produce good quality grapes can still benefit from a lower leaf removal of 50%. In warmer climates where risk of sunburn is higher, early basal defoliation is preferred to allow foliage to grow back, protecting the grapes from damaging sunlight exposure close to harvest.

PRUNING TIMING

Standard Pruning and Climate Change Climate change is impacting the global winemaking industry. Some vineyards are threatened by droughts, periods of intense rainfall, and heat waves, among other changes[22]. Regions with warming climates cause grapes to ripen at a faster pace, leading to accelerated sugar accumulation, higher pH, and the depletion of aromatic and phenolic compounds, which change the aromatic profile of the wine[22,23]. Therefore, it is necessary to implement solutions to mitigate these effects.

TABLE 1: COMPARISON OF PRUNING TIMING. Impact on grape characteristics caused by different pruning timing techniques[22,24].

	Winter Pruning	Double Pruning	Late Pruning
Yield	High	High	Low
Bunches/vine	High	High	Low
Berry mass	High	Medium	Low
Cost	Low	High	Low
TSS	High	High	Low
TA	Low	Low	High
Phenolic substances	Low	Low	High
Susceptibility to *E. lata*	High	Low	Low

One potential solution in warming climates is to change the timing of pruning. Double pruning and late pruning are strategies used to delay sugar accumulation and limit yield, countering the effects of warming climates[22,24]. Traditional pruning techniques involve pruning the grapes to the desired bud count in the winter while they are dormant, but this technique is susceptible to warming climates[24]. Double pruning involves an initial pruning during dormancy, then a second pruning in the spring[22]. When late pruning is used vines are left unpruned during the winter months[23,24]. Pruning occurs in the late spring or even early summer after buds burst and leaf growth has started[23,24]. In the following sections, double and late pruning will be explored and compared in further detail. Their impacts on grape characteristics are shown in Table 1.

Double Pruning

Double pruning is a technique used to combat the effects of warming climates and fungal infections, without a large cost increase[22,25]. This technique requires vines to be either mechanically or manually pre-pruned in the winter, then manually spur pruned in the spring[22]. Pre-pruning shortens the canes to a uniform length, and the second pruning is done to preserve the number of buds wanted by the vigneron, for which the standard is two-bud spurs[22]. The timing of pruning can vary between vineyards, with pre-pruning performed during dormancy, and the second pruning occurring between March and May in the Northern Hemisphere[22,25].

Double pruning has been found to delay budburst and harvest, helping to mitigate the effects of warming climates[22,26]. Berry yield, berries per vine, clusters per vine, and cluster weight were all reduced[22]. However, the yield reduction can be controlled by removing less than 10% of leaf area[22]. If more than 10% is removed, the ripening of the berries accelerates, countering the effect of double pruning[22]. Bud fertility was significantly lower when vines were double pruned compared to standard winter pruning[22].

Double pruning also affects the quality of the grapes. Double pruning decreased the pH and TSS of the berries; however, there was an increase in total acidity and phenol concentration[22,26]. Also, the concentration of anthocyanins in the grapes increased due to double pruning[26]. The wines made from double pruned grapes were found to have 0.7% less alcohol than the standard pruning methods and increased phenol concentration[22]. This method is effective in delaying the ripening of grapes, which produces wines with lower sugar content, lower pH, and higher total acidity[22].

Many vineyards are affected by Eutypa dieback, a disease in grapevines caused by the fungus *Eutypa lata*[27]. Pinot noir, Merlot, and Cabernet Sauvignon are all grape varieties that are susceptible to *E. lata*[28]. Rain and wind spread *E. lata* spores onto pruning wounds[27]. When the spores land on exposed wounds, they are spread through the vine cordons, causing internal tissues to die and producing toxic metabolites[27]. The disease cycle of *E. lata* can be seen in Figure 5. The toxic metabolites play a role in reducing bunch size and causing uneven berry ripening[27]. Double pruing can help reduce the negative effects of *E. lata* by lowering the risk of spores spreading through rainfall[25]. It has also been found that pruning wounds made in spring are susceptible to infection for a shorter period of time[25]. The disease causes vascular discolouration of the cane, but this does not always correspond to the presence of the fungus[25]. When *E. lata* was inoculated onto plants, it was found that the vascular discolouration stretches up to 14 cm away from the wound, but the fungi were reisolated only up to 2 cm away from the wound[25]. This limits the region that needs to be removed by pruning[25]. Overall, double pruning can be effective in reducing the presence of fungi in the grapevines, reducing economic loss for vignerons[25].

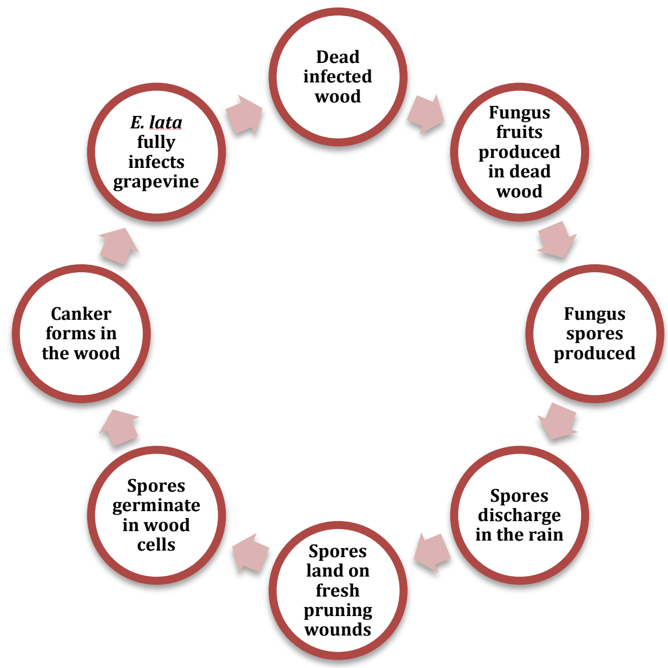


FIGURE 5: *EUTYPA LATA* DISEASE CYCLE. Double pruning reduces the number of fresh pruning wounds in the spring, when grapevines are most susceptible to spores discharged in the rain. This pruning timing can therefore reduce the prevalence of *E. lata* infection, decreasing the overall severity of the disease later in the cycle. Adapted by authors[3].

Late Pruning

Late pruning is an alternative method used to counter the effects of warming climates on grapevines[7,24]. Late pruning occurs after the budburst in late spring or early summer and works by restarting growth for the season later in the year[24]. When no pruning occurs, the growth of the vine is concentrated at the top of the canes from previous seasons[24]. As a result, the buds at the base of the cane—basal nodes—remain dormant[24]. When the upper growth is pruned, the basal nodes are no longer inhibited[24]. The vine restarts growth by relying on carbohydrates stored in the trunk from previous seasons[24].

Late pruning effectively alters the fruitfulness and the phenology of Pinot noir vines. Late pruning delays growth until later in the spring when tempatures are warmer, increasing growth efficiency[24,29]. Despite the extended time difference between the methods of winter pruning and late pruning, the greater growth efficiency caused by late pruning reduces the difference between winter pruning and late pruning harvest dates[24,29]. Studies have found that late pruning causes greater delays in the harvest when it is applied over successive seasons, delaying ripening to a cooler time and reducing sugar accumulation[24].

Late pruning significantly decreases yield and fruitfulness of the vines[4,23]. This is caused by the reduction in the number of buds, the removal of more fruitful buds[4,24], and overall smaller berries[23,24]. In contrast, the reduction in yield is paired with an increase in grape quality[23,24]. During harvest, it has been found that vines that are treated with late pruning have lower levels of TSS and higher levels of TA[24], traits that are ideal for sparkling wines made with Pinot noir grapes[23].

Alterations of the grapes' characteristics caused by late pruning produce wines of greater quailty[30]. Late pruning increases the tartaric acid concentration in the Pinot noir grapes, resulting in an increase in wine acidity[24,30]. Moreover, late pruning significantly increases the concentration of phenolic substances and decreases the TSS of Pinot noir grapes at harvest[24]. This improves the sensory characteristics of the wine produced, including the colour, taste, mouthfeel[24], and aroma[30].

CONCLUSION

Based on the literature, we have developed a theoretical canopy management strategy for optimizing the quality and yield of Pinot noir grapes. We recommend utilizing a vertical training system as there is evidence that vertical systems produce Pinot noir grapes and wines of a superior quality. Cane pruning is the traditional pruning technique for Pinot noir, though it is done by hand and incurs high labour costs[10]. Spur pruning is a more economical option since it requires less manual labour and is easier to mechanize[13,14]. However, due to low Pinot noir crop yields, there is some hesitation in adopting this technique[13,14]. Despite the development of innovative mechanical pruning alternatives, vignerons should be judicious when considering a transition. We suggest either remaining with manual cane pruning or testing different methods to find an ideal combination.

To further improve grape and wine quality, we suggest altering the microclimate around the fruit clusters by performing full basal defoliation in cooler, more humid climates. This will improve air circulation around the grapes to help prevent fungal infections while ensuring increased sunlight exposure[20,21]. This technique has been shown to improve colour intensity and stability, wine flavour, and aroma[20,21]. The impact of basal defoliation on yield is minimal[20], causing the grapes to be higher quality while preventing loss in quantity.

While winter pruning is the industry standard, we recommend using double pruning because of its ability to mitigate the effects of warming climates and infection by *E. lata*[22,27]. Additionally, the grape quality is not negatively affected and produces high quality Pinot noir wines. While late pruning is also able to mitigate the effects of warming climates, it produces a lower grape yield with characteristics that are better suited for sparkling wines rather than Pinot noir wines[23].

While these recommendations theoretically produce the optimal Pinot noir grape, vignerons need to consider the unique climate, terrain, pests, and other challenges of their vineyard when developing canopy management strategies. Vineyard-specific variations on our canopy management strategy will help to optimize grape quality in different climates and vineyards.

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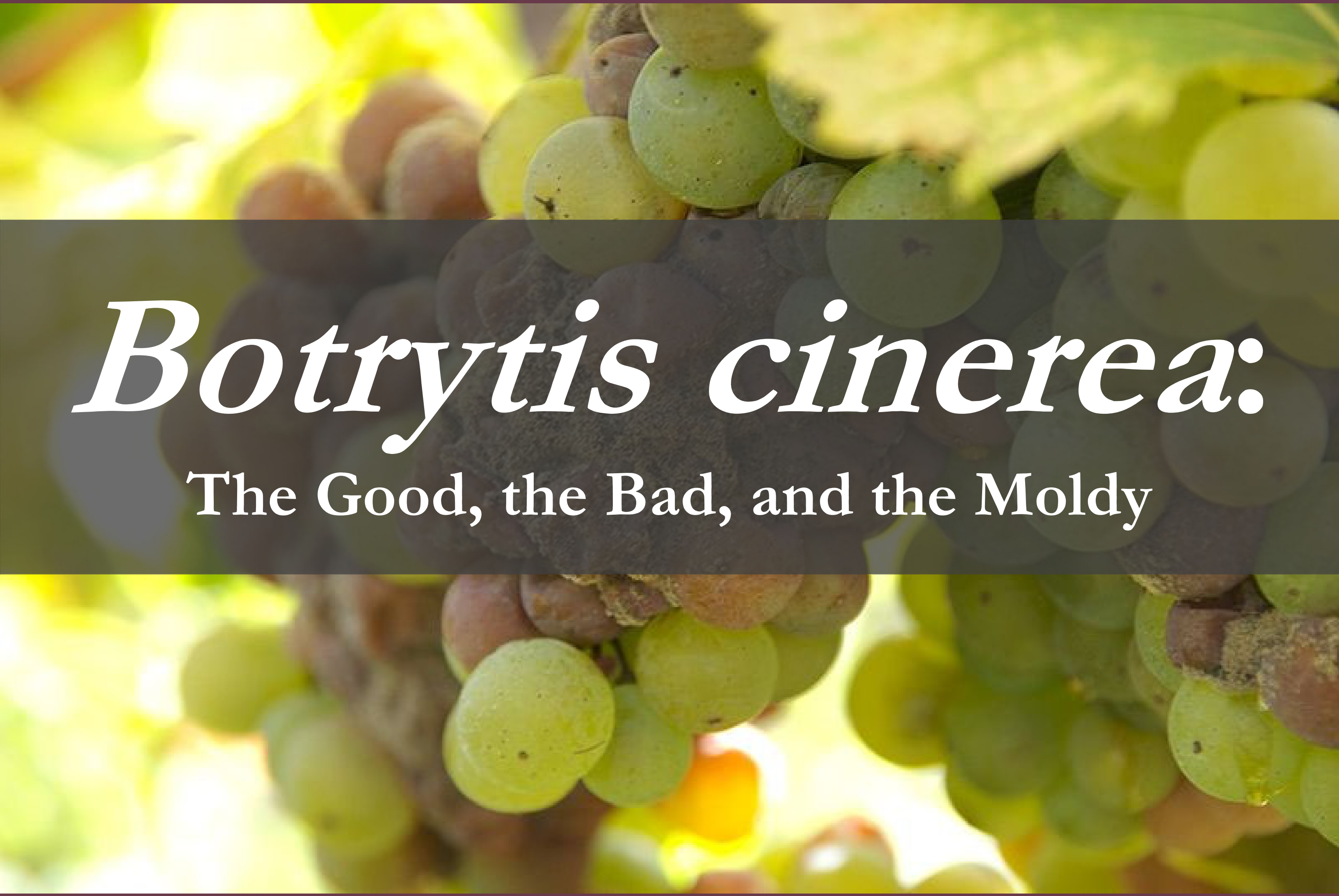
COVER IMAGE

Laurel Bank Wines. Pinot Noir harvest [Internet]. Available from: https://search.creativecommons.org/photos/63ee5c29-a06f-48f2-9029-72bc45d88017



Botrytis cinerea:

The Good, the Bad, and the Moldy

Christina Brinza, Grace Burgess, Sam Lu-Sullivan, Ashlyn Roy, Dua Saqib, Keshikaa Suthaaharan

Botrytis cinerea is a widespread fungal plant pathogen that causes bunch rot in grapes. It is responsible for extensive agricultural and economic damage. In particular cases, however, this fungus can lead to a milder infection known as noble rot that produces the delicacy known as botrytized wines. During noble rot, *B. cinerea* alters the chemical profile of grapes through various biochemical interactions, and thus impacts the flavour profile of the wine that will be produced.

Currently, botrytized wines contribute significantly to the wine industry and economy, but the production process is challenging due to the specific environmental conditions required for successful noble rot development, and the ever-present threat of bunch rot. Future research may allow wine producers to optimize methods to artificially introduce and control noble rot infections in order to produce high-quality botrytized wines.

Cover image is of botrytized grapes from the Sauternes region[1].

INTRODUCTION

Hundreds of years ago, in Sauternes, a region in France, the owner of a chateau left on a trip and told his servants not to harvest the grapes cultivated on his estate until he returned. Unfortunately, his trip was delayed, and the berries became infected by a mysterious pathogen and shriveled up before he arrived back at the chateau. The owner ordered the servants to harvest the grapes anyways, and produced an unexpectedly sweet, honey-like wine. He found this wine to be so good that he proclaimed that, from then on, they would only harvest the shriveled berries. This apocryphal story from Teissedre and Donèche[2] illustrates one of the many origin stories of a specialty beverage known as botrytized wine.

The organism present on the berries was *Botrytis cinerea*, one of the most prevalent agricultural fungal pathogens in the world[3]. In rare situations, *B. cinerea* causes **noble rot** (seen in Figure 1), a mild infection. Wines produced from noble rot-infected berries are referred to as **botrytized wines**, and are prized for their high sugar content and sweet fruity aroma[2]. But more often, *B. cinerea* leads to **bunch rot**, a devastating infection that can destroy crops[4]. It affects over five hundred different plant species, including agriculturally and economically important crops such as tomatoes, strawberries, and grapes[3]. The fungus attacks the stems, fruit, flowers, seeds, and leaves of plants[3]. It is a **necrotroph,** an organism that attacks and kills the cells in the host, eventually causing the plant to die[5]. Its spores can be carried on the wind or in water and can survive for long periods on crop debris[3]. This gives them the ability to spread quickly and effectively, dispersing across vast tracts of land[3]. *B. cinerea* can attack plants at any stage of development, from seedlings onwards, and can impact the fruits even after they have been harvested[3]. The risk of infection increases after insect attacks, or when excessive rainfall causes the skin of the grapes to split, exposing the flesh inside and promoting the development of bunch rot[6,7]. During the development of bunch rot, the fungus grows on the surface of the grape, appearing as a gray mold that spreads easily throughout an entire bunch[6]. Unlike other fungi, *B. cinerea* is able to penetrate unperforated grape skin in very humid conditions[8]. At the start of infection, grapes become brown and soft[8]. With sufficient humidity, bunch rot can spread rapidly through clusters[9].

This establishes an interesting dichotomy between the beneficial fungal infection in our story, known as noble rot, and the devastating infection known as bunch rot, also caused by *B. cinerea*. *B. cinerea* bunch rot is estimated to cause billions of dollars' worth of damage to the global agriculture industry every year, of which a significant fraction is attributed to the wine industry[10]. Chemicals targeting *B. cinerea* account for 10% of the global fungicide market, with at least half being used in the wine and grape sectors[10]. In addition to the cost of control strategies, bunch rot can cause extensive product loss and reduced wine quality[10].

FIGURE 1: BOTRYTIZED BERRIES A grape bunch from the Gironde region of France that have been infected with noble rot (*B. cinerea*)[11]. The infected grapes have turned a rosy pink while the unaffected grapes remain green.

Yet, despite the economic damage *B. cinerea* causes, botrytized wines produced as a result of noble rot are regarded as a delicacy around the world for their unique flavour and sweetness[2]. This sweet drink was traditionally produced in three regions: Tokaj, Hungary; Rheingau, Germany; and Sauternes, France[2]. However, the production of botrytized wine has since spread to other parts of the world, including Italy, Australia, New Zealand, South Africa, and California[12]. Although its overall economic value has been poorly assessed[2], botrytized wines are a major export from these regions, and individual bottles can sell for over 500 euros[10]. In fact, the most expensive white wine on record was a bottle of 1811 Chateau D'Yquem, a botrytized wine that sold for a six-figure sum in 2011[13].

This brings us to the question: how does a fungus that can kill its host create a delicacy that is so influential within the wine industry? Characterizing the relationship between *B. cinerea* and the grape is critical for understanding how these interactions contribute to the unique flavours of botrytized wine.

HOST-FUNGUS INTERACTIONS

B. cinerea may either produce pre-harvest symptoms or remain asymptomatic until grapes have been harvested, making it a versatile vineyard pest[3]. In the vineyard, *B. cinerea* can survive on dead vines and leaves during the winter without spreading disease, and can release spores in the spring to infect surrounding grapes[14]. Host and chemical defenses limit the spread of early-season infections so the pathogen lies dormant until the grapes ripen in autumn, and then proceeds to kill the grape as host defenses decline as the berry ages[14,15]. Once the conidia spores land on the grape, they produce filaments (hyphae) which spread across the grape skin and form tubes called appressoria, structures that allow the fungus to penetrate the external waxy layer of the berry[16] (Figure 2). These appressoria further help adhere the spore to the surface and secrete multiple **cell wall degrading enzymes** (CWDE), which allow the fungus to enter the grape cells[14].

Once inside the cell, *B. cinerea* releases proteins and small ribonucleic acid molecules that suppress host immune defenses[17]. This ultimately allows the fungus to grow for a longer period of time before killing the host[17]. After this time, *B. cinerea* releases a series of chemicals in order to weaken the host, including reactive oxygen species (ROS), unstable molecules that can easily damage essential proteins and DNA[15]. In response to infection, however, the plant also releases a burst of ROS (also called an oxidative burst) that is required to initiate its defense mechanisms[15]. The oxidative burst also causes the death of the grape's own cells at an earlier stage of infection in an attempt to limit the fungus' access to water and nutrients[15]. However, as a necrotroph, *B. cinerea* actually benefits from this oxidative burst for its own growth, as the overall increase in ROS ultimately leads to increased host cell death, and thus greater susceptibility to the fungus[14].

In addition, *B. cinerea* secretes oxalic acid, which contributes greatly to infection by stimulating the production of CWDEs[14]. CWDEs further lead to cell lysis, when the cell bursts and dies[14], and are also thought to play a role in the hijacking of the host cell wall for nutrients[18]. Oxalic acid reduces defense responses of the grape cells, increases the production and activity of fungal enzymes, and promotes programmed cell death in the berries[14]. Many fungal toxins such as botrydial, which causes chlorophyll loss and cell collapse, are also produced in infected tissue[16,18]. Various fungal signalling pathways initiated at the onset of infection regulate the production of these toxins and chemicals[14]. Ultimately, host cell death is mediated by the host and fungal-originating ROS, as well as the toxins and enzymes released by the fungus during infection[15].

Unlike the response of *B. cinerea* to the grape, much less is known about the response of the grapevine to *B. cinerea*. The main plant defense implicated in *B. cinerea* infection is pathogen-associated molecular pattern (PAMP)-triggered immunity[19]. This initial detection triggers various signalling pathways that activate generalized plant defense mechanisms to strengthen the grape's immunity to *B. cinerea*, such as the production of toxins, cell-wall reinforcements, and other defensive molecules[19]. Interestingly, young leaves and flowers, as well as mature berries, are more susceptible to infection than green berries and berries that have just started to ripen (commonly referred to as the veraison stage of growth)[19]. Berries in the veraison stage can activate a defense mechanism that can effectively stop the infection process. In contrast, mature berries activate a different defense mechanism in response to *B. cinerea*, which does not stop the infection[19].

PAMP-triggered immunity
Immunity that relies on the detection of evolutionary conserved molecular structures on pathogens (known as pathogen-associated molecular patterns, PAMPs). Recognition triggers cellular responses that activate the immune system[15].

If *B. cinerea* kills its host, how is it able to produce noble rot, an infection so mild that it does not compromise the integrity of the berry? Under the conditions that produce noble rot, splitting of the berry is less likely to occur, so the fungus remains on the skin and has less of an impact[20]. In noble rot, *B. cinerea* does not release as many toxins as it does in bunch rot[20]. The differences between noble rot and bunch rot are enough to create a sweet wine rather than produce a ruined crop.

Noble rot infection typically occurs during late harvest, around

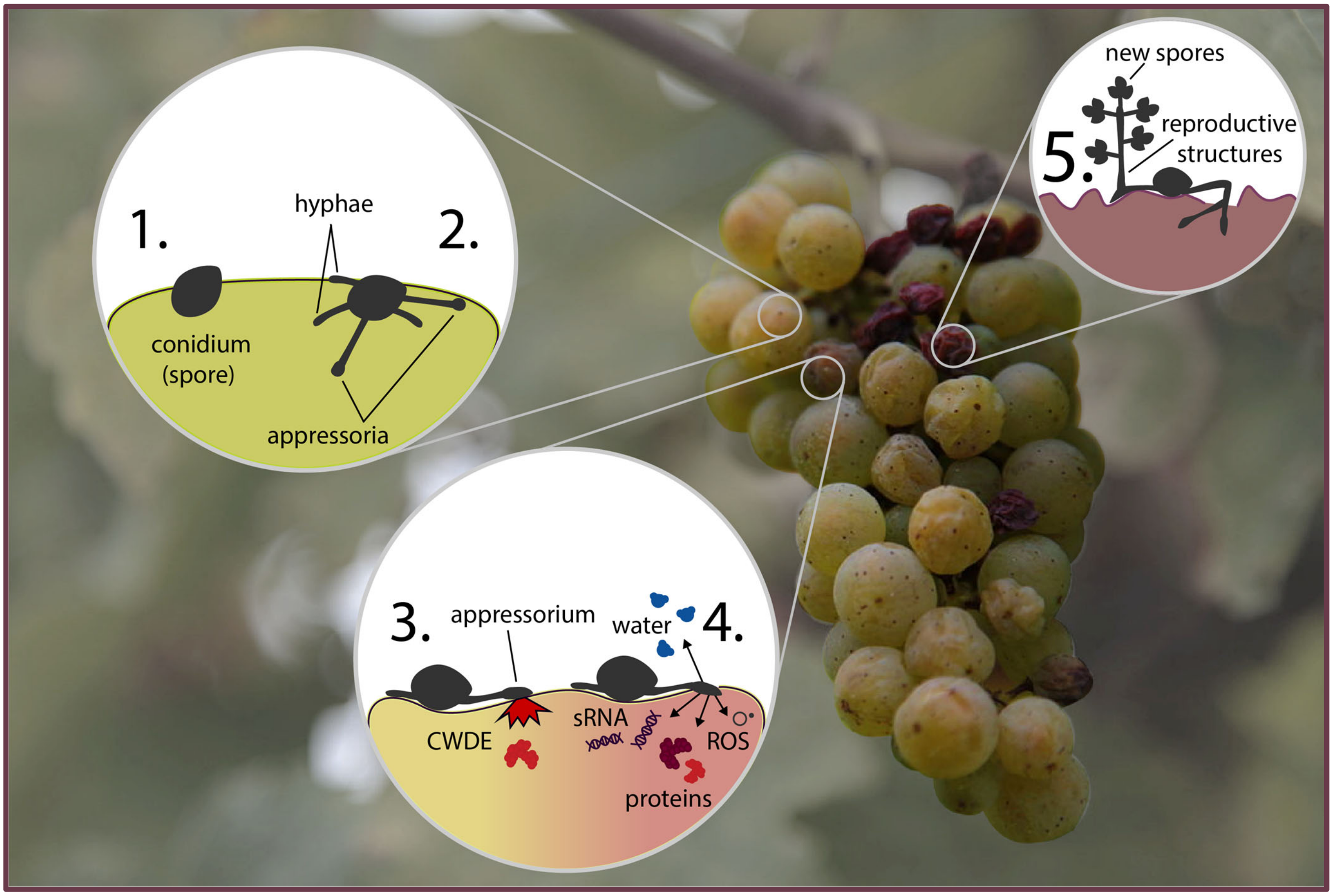


FIGURE 2: LIFESTYLE OF *BOTRYTIS CINEREA* ON GRAPES 1. Spores of *B. cinerea*, known as conidia, are released in the spring, summer, or fall and may attach to the skin of a grape berry. 2. Spores produce filamentous structures called hyphae, which have specialized cells called appressoria that are used for puncturing through the grape skin. 3. Appressoria secrete cell wall degrading enzymes (CWDE), which help degrade the cell wall of the berry and break the skin. 4. *B. cinerea* enters the cell and releases proteins, small RNA molecules (sRNA), and reactive oxygen species (ROS) which suppress host immune defenses. At the same time, water evaporates from the grape berry through the break in the skin, causing berries to dehydrate and take on a wrinkled appearance. 5. During the last stage of the fungus' life cycle, the reproductive organs develop and form new spores, which are released to infect nearby berries[15,16].

NOBLE ROT

Noble rot only occurs naturally under highly specific environmental conditions[12]. Regions like Sauternes, Tokaj, and Rheingau, which experience warm dry days and cold damp nights, are ideal for noble rot development and propagation[6]. However, the most famous sweet wine producing region is the Sauternes region, described earlier, which experiences five hours of sunlight, lower humidity, and high temperatures (above 26 °C) during the day, and six hours of darkness, higher humidity, and cold temperatures (below 15 °C) at night[21]. This humidity is usually provided by mist from nearby lakes and rivers in the morning[22]. After this moistening, warm days are needed to dry the grapes to prevent bunch rot[6].

September and October, when grapes are fully ripe[23]. There are two stages of noble rot development: *pourri plein* and *pourri rôti*[24]. The first stage is *pourri plein*, in which grapes begin to brown right after the fungus penetrates the grape skin, followed by the *pourri rôti* stage in which the grape is dehydrated and the juices and sugars are concentrated[24]. Grapes are individually harvested during the *pourri rôti* stage[24]. Due to the dehydrating quality of *B. cinerea*, more botrytized grapes are required to produce the same amount of wine as uninfected grapes[21]. Additionally, specific grape varieties are required, and the berries must either be fully ripe or overripe at the time of infection with *B. cinerea*[12]. Under these conditions, *B. cinerea* releases chemicals into the grapes that produce the characteristic flavour of botrytized wines[2].

THE CHEMICAL IMPACT OF *B. CINEREA* ON WINE FLAVOUR

In **noble rot** infection, *B. cinerea* intensifies the sweetness level of the wine and adds flavour complexity[22]. When *B. cinerea* spores land on the fruit, the appressoria break through the skin and into the berry pulp, drawing water away through the berry skin and causing the berries to dehydrate[25]. The loss of water concentrates the sugars in the berries, and begins to alter the grape's acidity[26].

Biological processes in fungal and plant cells, such as energy production or the activation of plant defense systems, produce chemical byproducts called **metabolites** that influence the sweetness, moisture content, and flavour profile of the grape[27]. Multiple metabolites are observed in higher concentrations in botrytized berries as seen in Figure 3[28]. In the first category, there is an increase in three compounds: proline, arginine, and alanine[28]. Proline directly activates some plant defenses, and is also a major component of proteins that play an important role in cell wall resistance under stress[28]. Arginine is also part of more complex defense molecules, and alanine is involved with the regulation of the movement of water into and out of plant cells, and also accumulates during plant defense against *B. cinerea*[28]. This is important for botrytized grapes, as the fungus reduces water intake into cells and consequently shrivels the berries[28].

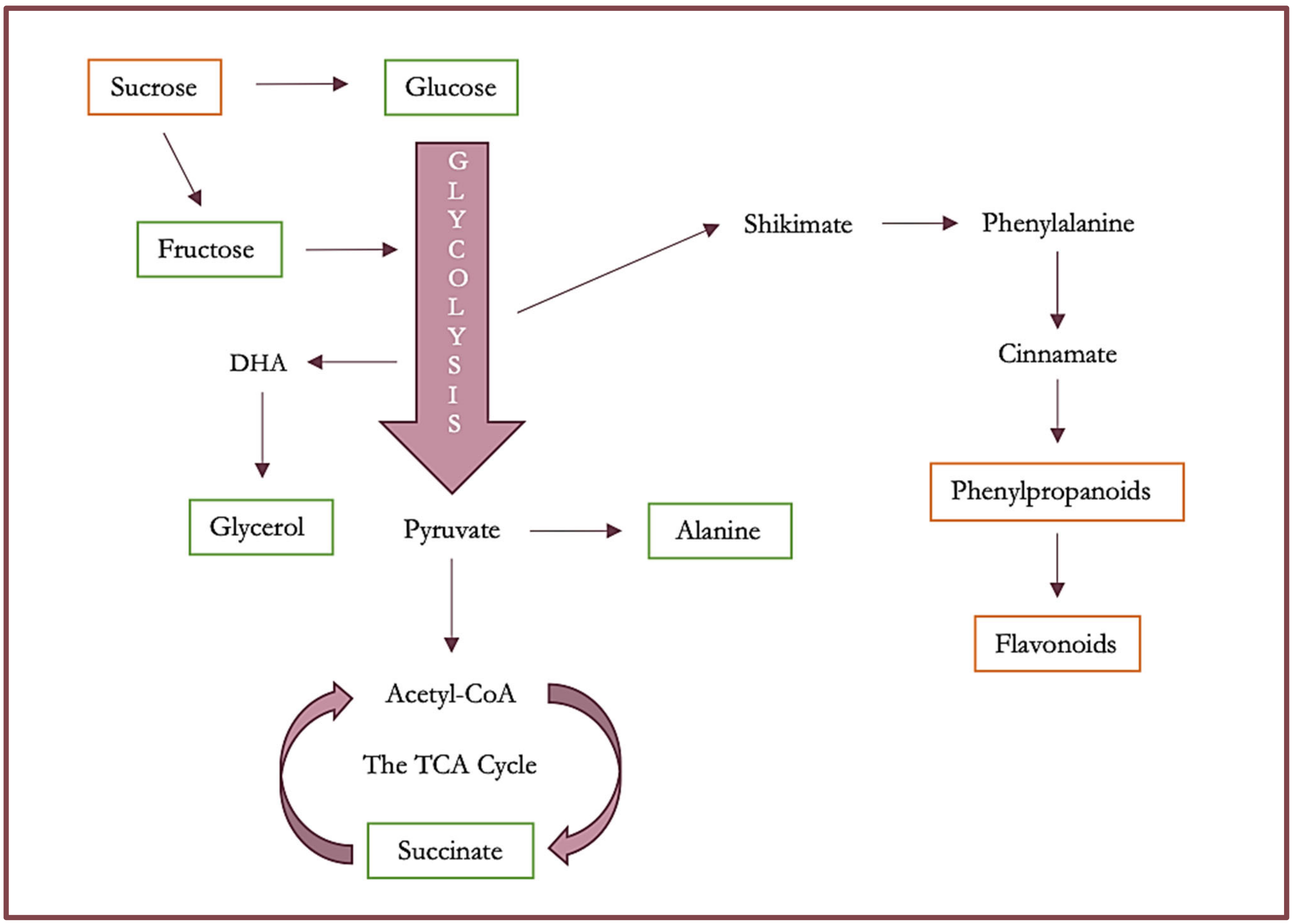


FIGURE 3: VARIATIONS IN METABOLISM OF NOBLE ROT AFFECTED BERRIES There are several changes that can be observed in the metabolism of botrytized grapes. This flowchart depicts these pathways; products that are more highly concentrated in botrytized grapes are outlined in green, and those that are less concentrated are outlined in orange. Sucrose is broken down into the simple sugars, glucose and fructose. These sugars are used for energy production through a series of reactions collectively known as glycolysis. Docosahexanoic acid (DHA) branches off from this process and forms glycerol in botrytized grapes, although the normal product of glycolysis, pyruvate, is still produced. This product then goes into the tricarboxylic acid (TCA) cycle, which is a normal component of metabolism, but one intermediate called succinate forms in higher than normal quantities. Another offshoot of glycolysis produces flavonoids and phenylpropanoids, which are degraded during the immune response to noble rot in botrytized grapes. Alanine is also produced in higher concentrations as an offshoot of glycolysis[26]. Intermediates of these reactions are shown for context.

The plant's defense system also partially or completely breaks down many compounds in the categories of flavonoids and phenylpropanoids[28]. **Tannins** are a recognizable category of flavonoids that impact the bitterness and mouthfeel of wine[29]. Depending on the grape varietal, the concentrations of these compounds can be impacted when infected with *B. cinerea*[30]. The fungus also increases the production of the reddish pigment **anthocyanin** in the grapes, causing botrytized grapes' typical blush-pink colour[30]. During fermentation into wine, highly scented compounds called thiols are produced in greater quantities from **thiol precursors** that are prevalent in botrytized grapes, creating a more aromatic and therefore desirable wine[30].

The metabolism of nutrients by the fungus itself also impacts the flavour of wine. *B. cinerea* generates simple sugars (glucose and fructose) for energy production and growth by injecting an enzyme that breaks down the grape's stores of **sucrose**[28]. As a result, the amount of sucrose in botrytized berries is decreased relative to healthy berries, but the concentrations of glucose and fructose are increased, which explains the sweet character of botrytized wines[28]. Two carbohydrates, **glycerol** and **gluconic acid**, are metabolites of *B. cinerea* that are found in high concentrations in the skins of botrytized grapes. *B. cinerea* secretes an enzyme called glucose oxidase into the plant to turn glucose into **gluconic acid**, giving the wine its characteristic honey aroma[28]. **Glycerol** is an alternate product of glycolysis, the process that most cells use to break down sugar[28]. It tends to give wine a more viscous texture that is indicative of high quality in wine-making[25]. The fungus itself also inserts enzymes that degrade sour compounds like tartaric acid, reducing sourness to bring the sweet taste of the wine to the forefront[25].

The development of *B. cinerea* induces the grape to produce chains of sugars, which have antifungal properties and inhibit fermentation to increase the acetic acid concentration of the berry[23]. This may add to the complexity of the flavour if balanced by other components in the wine, but can also overpower other desirable flavours if the sugars dominate the wine composition[26]. Botrytized wine also has a higher concentration of chains of sugar molecules called **oligosaccharides** and contains lower **alcohol** content[27]. These findings suggest that fermentation may occur more slowly in botrytized wine than in other wines[27].

Furthermore, the fungus releases enzymes that can break down components of the berries' cell walls and interact with acids in the berry to activate metabolic degradation[30]. As a result, grapes must be harvested before they are overly ripe, so that some acidity is maintained during and after the fermentation process to ensure a complex balance of sweet and sour elements in the final product[30]. Other enzymes may increase the concentration of flavourful proteins in the berry juice[30].

Through all these changes in the composition of botrytized wine, a unique flavour profile is created[26]. Several common traits that are associated with botrytized wine include a honey aroma, and descriptors such as flowers and dried fruit. Some medicinal aromas, such as notes of wet absorbent cotton, may also be detected[26]. These **metabolites**, produced as a result of the infection, form the unique flavours of botrytized wine that are so highly prized in viticulture[22]. Despite their value, there is still no way to artificially produce botrytized wine on a commercial scale, as the strict environmental conditions required for the successful inoculation and development of noble rot are difficult to replicate[30]. Winemakers who produce botrytized wines naturally must maintain the delicate interplay between the fungus and the plant, and remain vigilant to ensure that conditions favour **noble rot** rather than **bunch rot**. However, the financial risk associated with the possibility of bunch rot in botrytized wine cultivation may decrease as our understanding of *B. cinerea* improves over time[23].

FUTURE DIRECTIONS

B. cinerea can produce drastically different infection outcomes, based on the environmental conditions. It releases enzymes which break down the cell wall and suppress host immune defenses, leading to the infection commonly referred to as bunch rot[16,17]. While much research has been done on the pathogenesis of *B. cinerea* on grapes, little is known about the response of the grapevine to *B. cinerea* infection[19]. It is known however, that the defense system of younger berries are more effective against *B. cinerea* than that of mature grapes[19]. Based on our analysis, additional research may prove useful to discover a common trait in grapes which develop noble rot.

Investigating the chemicals produced gives us insight into how these flavours and characteristics form in the wine, for a more holistic understanding of wine development. As stated previously, noble rot causes significant dehydration of berries. Metabolites produced by the plant's defense system or released during fungal growth degrade flavonoids such as tannins, thus reducing the bitterness of wine and increasing hue intensity[28,29]. In addition, it breaks down sucrose into simpler sugars and degrades acids, increasing botrytized wine's sweetness[28]. It has also been documented that fermentation is slowed in botrytized wines[27]. However, this does not negatively affect the chemical profile of these sweet wines as lower alcohol content is often required for high sugar content in wines[30]. Numerous other chemical changes in the grape juice contribute to the unique flavour profile of botrytized wine. These studies provide information about the altered chemical profile of botrytized wines. This information, coupled with further research on the impacts of *B. cinerea* on flavour, could lead to the development of novel artificial methods to produce wines with similar tastes and characteristics as botrytized wines. Importantly, optimizing artificial methods of production could greatly reduce the risk of bunch rot occurring during the growing season.

In particular, there is interest in experimentally replicating environmental conditions of regions where noble rot must otherwise be artificially inoculated after harvesting in different climates[31]. New techniques of inoculating *B. cinerea* on the grapes are also being tested out in a California vineyard's botrytized wine production process, by growing mold spores in a laboratory and applying them to harvested grapes in a controlled environment for weeks before aging the wine[26].

However, due to the possibility of bunch rot infection, which could wipe out the whole grape harvest, many vineyards remain hesitant to allow experimentation with their traditional farming and production practices. As stated before, *B. cinerea* causes both noble rot and bunch rot, and the regions in which noble rot occurs naturally are rare[32]. Understandably, this reduces its appeal to researchers for further study, and hinders the potential widespread application of noble rot to vineyards. But if these important limitations can be addressed, and noble rot infection can be produced reliably, *B. cinerea* could become a highly useful tool in viticulture, rather than the feared scourge of vineyards.

CONCLUSION

Although *B. cinerea* is typically seen as a detrimental pathogen that can decimate an entire vineyard, infections that form under specific environmental conditions may result in grapes with complex, concentrated flavours that can be processed to make highly prized sweet wines. The eventual development of innovative new production methods could make it less risky for vineyards to create new varieties of botrytized wine. Noble rot is just one example of how versatile and adaptable viticulture is to our ever-evolving world, as well as an important lesson that even creatures we consider pests can create something sweet.

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To Buy or Not to Buy:

The Impact of Wine Labels on Purchase Intention

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The challenge of creating an effective and attractive label to increase purchase intention, and therefore sales is an issue many wine sellers have experienced. Small differences in branding can make-or-break a consumer's decision to select one bottle over another. Thus, the unique design of wine labels must be carefully crafted to include optimal descriptors and visual components. This article explores the key design aspects of a wine label and its complexity in the marketing of wine.

The importance of a wine label to create a positive first impression should not be understated. This article examines extrinsic cues found on both the front and back labels that affect whether a consumer will purchase the product. The front label predominantly attracts the attention of a consumer and is emphasized with specific considerations for key information for consumers, processing fluency, and semiotics. The back label complements the front and provides specific and detailed information to further guide purchasing decisions. Both components come together to form the unified brand and set up the ultimate sales pitch to the targeted consumer.

INTRODUCTION

Although many people do not realize it, an abundance of research, planning and knowledge is required to ensure that a wine bottle makes it off the shelf and into a consumer's cart. Unlike other products such as apparel, wine is unique in that consumers are usually unable to experience the product prior to purchasing. The degree of variability between wines on the market is significant. Wines vary drastically in their **organoleptic characteristics**, including tastes, textures, aromas, and appearances. Yet, a consumer cannot rely on these characteristics to inform initial purchasing decisions regarding wine.

A consumer's attraction to a bottle of wine, and therefore their **purchase intention**, are influenced by several factors. These factors can be categorized into one of two groups: intrinsic or extrinsic cues. Intrinsic cues relate to the physical attributes of the wine itself, are unable to be changed without chemically altering the wine. Intrinsic cues include, but are not limited to, a wine's mouthfeel, flavour profile, and appearance[1]. Extrinsic cues relate to the product but are not directly part of it; these factors can be modified without altering the wine itself. A wine's corkage method, price, brand, and most significantly, label design, are examples of extrinsic cues (Figure 1). A wine bottle's label is the primary source of information for consumers, containing many extrinsic cues, including nutritional information, country of origin, age, and year of harvest[1]. Additionally, images on wine labels can provide information and induce a targeted emotional response among consumers. These influential cues are found on the front and back labels of the wine and help a consumer better understand the product.

FIGURE 1: EXTRINSIC CUES COMMONLY FOUND ON WINE LABELS. Many extrinsic cues are used to convey information to consumers. This includes information directly related to the wine as well as brand identity, for instance (Image adapted from PxFuel).

Most of the research regarding marketing is focused on the understanding of label preferences. This is because a wine's label has been shown to be the most important factor in purchase intention; it not only conveys key information about the wine but also affects a consumer's perception of a brand and the price they are willing to pay[2–4]. A study by Sàenz-Navajas et al.[3] demonstrated that the most important extrinsic cue which influenced willingness to purchase was information found on the label. The top 13 of the 22 cues studied were found on or related to the label such as images, text (including information such as country of origin), and label colour. Furthermore, not only were wines with specific indicators chosen more often, but participants were also more willing to pay a premium for these products. It is clear just how important a well-made label can be.

Our research investigates how front and back wine labels influence a consumer's purchase intention. Within our

Organoleptic characteristics: properties that induce an experience through the senses.
Purchase intention: a consumer's willingness to buy a given product at a specific time or in a specific situation.

research, we focus on a non-expert buyer which we have defined as individuals who demonstrate interest in the product and both purchase and consume wine but are not involved in a wine-related industry.

FRONT LABEL

Packaging design is a communication medium that strongly influences point-of-purchase decisions[4]. This is especially relevant in the wine industry, as consumers often cannot taste the product prior to purchasing. While one can seek guidance and wine expertise through journals and specialized shops such as the Liquor Control Board of Ontario (LCBO), non-expert consumers tend to form their first impression of a wine by reading the labels in the store [2]. The front label is typically the first line of communication to entice consumers[2]. It is important that the label meets the standard regulations set for alcoholic beverages, while remaining visually appealing to stand out from the competition.

Although you might assume that consumers would do their due diligence before buying a relatively expensive beverage such as wine, in reality, many consumers only use a small amount of information available on a package to make a decision[2]. Therefore, for a front label to be effective in increasing the purchase intentions of consumers, it should be simple. 'Simple' in this case, refers to including only the most relevant information and presenting it in such a way that one can easily process it.

A survey conducted by Barber and Almanza[2] determined whether the front label increases the chances of a wine being purchased and what is the most important information on the label.. The questionnaire described a variety of packaging characteristics such as bottle shape, color, front and back label design, and information provided. Results showed that the most important characteristic was the country of origin (COO) on the front label. Additionally, the vintage and the brand name tied with the second highest score for importance.

Country of origin is of huge importance in the wine industry. In fact, it has been suggested that wine is "the most differentiated of all agriculturally-based consumer products"[5]. COO can affect consumers' overall view of the product based on their perception of a country's strengths and weaknesses in the production and marketing of wine[5]. Thus, the perceived quality distinctions among wine producers in different areas have led consumers to pay premium prices for wine[5]. For instance, consumers may gravitate towards wine from the top wine-producing countries in the world—specifically, Italy, France, and Spain—as these traditional producers have good reputations and are associated with wines of higher quality[5]. However, consumer preferences for alcoholic beverages, especially wine, have changed drastically in the past decade. Globalization, mixed cultures, and economic changes have increased the prominence of new world wines from the USA, Australia, and Canada in the marketplace[5]. These new trends emphasize the need to develop new marketing strategies in world wine trade to meet new consumer preferences.

Similarly, vintage and brand name are two extrinsic cues that are also associated with wine quality. Vintage wine is made from grapes grown and harvested in one specified year, whereas non-vintage wines can include blends of grapes from different years. Vintage is often associated with 'Vintage Port', which represents wine produced from the best quality grapes in the best growing years[6]. Therefore, vintage wine may be perceived as old wine of particularly high quality, despite this often being a misconception. A strong brand is also advantageous in the wine industry. Wines with a strong brand are considered to be more appealing, enjoyable, well-known, trusted, and of higher quality[7]. More recognizable brands are often purchased based and familiarity of the brand, or the age of the wine are crucial pieces of information to include in the front label.

EYE-TRACKING One approach that has proven effective in wine label research is infrared eye-tracking. Researchers use this technology to simultaneously record pupil movement, eye fixation times, and pupil diameter while consumers are making purchasing decisions. These studies are performed in the interdisciplinary field of neuroeconomics, which seeks to explain the neurological mechanisms involved in decision making[8]. Eye-tracking is able to analyze unconscious and non-verbally reportable processes. As attention and gaze are partially involuntary responses to stimuli, researchers can collect more accurate data[9].

FIGURE 2: TEXT-FITTING AND NON-FITTING IMAGES. The image on top represents an example of a text-fitting-label where the image displayed on the bottle matches the word "vineyard". The image on the bottom represents an example of a text-non-fitting-label where the image of the tree and bird has no explicit relation to the words placed on the label. These images were taken using a standard phone camera.

Fluency

While a simple and effective label may be key to good packaging design, other factors also increase purchase intentions of consumers. Specifically purchase intention, processing fluency can be a major driving force for a consumer picking a product[10]. Processing fluency is defined as the ease at which information is able to be processed and can be further broken down into cognitive and affective fluency. Cognitive fluency refers to the amount of effort that has to go into establishing a relationship between two or more pieces of information on a label[10]. Additionally, affective fluency refers to how enjoyable a person finds the process of interpreting all elements of a label.

It could therefore be predicted that the wine bottles resulting in the highest purchase intention have a balance between cognitive and affective fluency[10,11]. The ideal cognitive fluency would be one with a high value, as a person would be able to conserve mental resources when making a decision. For example, using only one font or a text-only label would yield a low cognitive fluency [10,11]. In contrast, a higher affective fluency would be ideal as this would reflect a greater level of enjoyment. To increase affective fluency, companies may opt to include pictures or elaborate designs on their label[10]. Such designs would not only increase the amount of visual information on the bottle but would also increase the amount of mental resources needed to make sense of the label—thereby increasing cognitive fluency. Thus, there is a trade-off between picking a label that is both cognitively fluent and affectively fluent.

A study conducted by Jaud and Melnyk[11] investigated this trade off by comparing the fluencies of text-only and text-and-image labels. The text-and-image label category was expanded to include text-and-image labels where the image either match or did not match the meaning of the brand name (Figure 2). These labels are referred to as text-fitting-labels and text-non-fitting labels respectively. Results from the study indicated that the text-fitting-label was ranked the highest in terms of purchase intention[10]. Additionally, no difference in purchase intentions was found between the text-non-fitting-label and text-only-label. This indicates that labels with either too high of an affective fluency or too low of a cognitive fluency can negatively impact the intent of purchase, while labels with a balance of affective and cognitive fluency can positively impact the intent of purchase[10].

Similar results were seen in a study conducted by Labroo, Dhar, and Schwarz[12]. Participants of this study were asked to first visualize a specific word and were then prompted to pick their preferred wine bottle, out of two possibilities. In this study there

FIGURE 3: FRONT LABEL CUE COMPARISON. Comparison of two wine labels. The *Ruffino* bottle on the left represents a more traditional label with a modern twist through the addition of subtle gold elements and small pops of yellow, blue and red. While primary colours can convey cheapness about the product, in small amounts, such as on this label, this effect may be mitigated. The *Twenty Bees* bottle on the right has a text-fitting image of a bee and high contrast colours of yellow and black. The cartoonish animal and vivid yellow used may signal a cheaper product, however the bottle may be more approachable and friendly relative to the *Ruffino* wine. This image was taken on a standard phone camera.

were two conditions—one where the visualized word and image on the bottle matched, and the other in which they did not[12]. In accordance with the first study, it was found that participants were more likely to prefer the first condition, where the word presented and image on the bottle matched. These results suggest that in order to maximize consumer liking and purchase intention of a wine bottle with an image, the image and text on the bottle should match in terms of meaning.

Label Design

In addition to processing fluency, purchase intention is also influenced by design elements such as images, colours, layout, and degree of complexity. These design elements are referred to as signifiers in the field of semiotics—the study of signs and their meanings. Semiotics has been employed in wine marketing research to better understand the message a consumer receives from a particular label[13]. Semiotics is also used in designing labels to minimize consumers' decision-making processes[14]. As previously discussed, this may happen by decreasing the cognitive fluency involved in the processing of the label. Signifiers convey messages to the consumer about the brand, product, and experience they might have when consuming wine[4,13]. Examples of signifiers and their meanings, referred to as the "signified" in semiotics, are discussed below and summarized in Table 1. Figure 3 provides an example of how these semiotic signifiers may be presented on a wine label.

Images

The presence of an image on a label does more than just influence cognitive and affective fluency. Through semiotics, the messages a particular image sends about a wine can be evaluated. Illustrations of chateaus, vineyards, coat-of-arms, and grape motifs tend to convey a sense of traditionality. Traditional labels are typically associated with trustworthiness and quality[13]. In contrast, label images that are paintings, photographs, and unusual and brand-irrelevant animals convey a sense of modernity[13]. While this can easily grab the attention of someone choosing a bottle of wine, there are trade-offs. Unusual animals and comical labels may convey a feeling of low quality and cheapness about the product[13,14]. While images have the potential to signify various qualities about a wine, ultimately, the choice is up to the consumer to decide what attracts them to the product. Some consumers enjoy taking risks with a potentially lower quality product because they are amused by the label. Alternatively, others enjoy a sense of high quality and prestige when purchasing a wine. It truly comes down to personal preference and the intended

SEMIOTICS: THE SIGNIFIER AND THE SIGNIFIED A sign can be reduced to two primary facets, the signifier and the signified. The signifier is the physical expression of the sign such as an image, or even a sound. The signified is the meaning attached to the signifier[15]. For example, the symbol of a gear (signifier) typically represents the settings function on an electronic device (signified).

consumption environment, such as alone or in a social setting[9]. Consumers are more likely to purchase a perceived high quality, traditional product for social consumption, while opting for a lower quality product for individual consumption[9].

Colour

A semiotic approach can also describe the effects of a label's colour scheme. White, yellowed white, and ivory labels communicate high quality, purity and tradition[13]. In combination with simple black text and subtle gold elements, a white label can also communicate modern elegance[15]. Bright, vivid, and primary colours can make a wine feel cheap[14]. Red tones convey passion and aggression, blues convey harmony and truthfulness, and yellows communicate optimism and joy[13]. Decreasing colour abundance while increasing colour contrast on the label may increase the perceived value of a wine, thus making it more attractive to a consumer[14].

Complexity of Designs

Another impactful quality of a wine label is how simple or complex it is. Although complexity is an abstract idea and may look different to individual consumers, it can be generally understood as how elaborate the label is. Complexity in design and the presence of embellishments can signify two contrasting ideas. First, complex designs can signify sophistication and seduction, qualities that a consumer may interpret as manipulative and superficial if not used appropriately[4]. Modern design and printing technologies have made the production of complex labels cheaper to produce which in some cases, can convey a sense of lower quality. A complex design can also provide a sense of imagination and creativity which may be

TABLE 1: SUMMARY OF COMMON SIGNIFIERS ON WINE LABELS.

	Signifier	Signified (meaning)
Image	Chateau, vineyard, coat-of-arms, grape motif, animal related to the wine or wine brand	Tradition, trustworthiness, quality[13]
	Paintings, photographs	Modernness[13]
	Unusual animals (unrelated to the brand), comical images	Low quality, cheap[14]
Colour	White, yellowed white, ivory	High quality, purity, tradition[13]
	Neutral, muted colours	Maturity[13]
	Black and gold design elements	Modern elegance[13]
	Bright, vivid, primary colours	Cheapness, lower quality[13]
	Red	Passion, aggression[13]
	Blue	Harmony, truthfulness[13]
	Yellow	Optimism, joy[13]
Design Simplicity/Complexity	Simple	Modernity, mass production, sobriety, honesty, wholesomeness, functionality, rigor, competence[4]
	Complex	Tradition, craftsmanship, sophistication, seduction, superficiality, hedonic, imaginative, creative[4]

intriguing to a consumer. On the other hand, simple designs are often associated with precision, honesty, and elegance signalling to the consumer that the brand is transparent about their product[4]. Sometimes, elaborate designs may be interpreted as a brand over-compensating for a potentially lower quality product. A semiotic study by Favier, Celhay and Pantin-Sohier[4] found that simpler wine bottles are preferred by consumers. Wine bottles with simpler labels had a higher purchase intention than wine with relatively more complex labels.

All aspects of a wine label, particularly the design features mentioned, contribute to the complete appearance of the label. Each facet works independently and in conjunction with the other facets to impress the consumer in some way. Semiotics is a valuable tool to gain insight on the individual messages each design features communicates to better understand the impression the label leaves on a consumer overall.

BACK LABEL

Similar to the front label, the back label of a wine bottle can also be an important factor in the purchasing decision of a non-expert. However, non-experts normally under utilize this section when selecting a bottle of wine due to the overwhelming amount of information present[16]. Examples of these fine details include, but are not limited to: sensory characteristics, special notes, nutritional value and ingredient information, COO, endorsements, and wine attributes[17,18]. Studies have shown that it plays a crucial role in the consumer purchasing process[17,18].

Charters, Lockshin and Unwin[19] discovered that 57% of participants claimed to rely heavily on the back label when selecting a bottle of wine. Moreover, they found that consumers placed the highest value on the taste description compared to all other factors. Although the small sample size and limited participant diversity make it difficult to generalize this study, it sparks curiosity into the importance of how wine brands should prioritize information displayed on the back label[19]. Additionally, Mueller et al.[20] assessed individual attribute preferences within different purchasing scenarios (Table 2). Their results demonstrated that almost all back-label information had a positive impact on consumer choice, with the most significant attributes being winery history, descriptive taste captions and suggested food pairings However, the inclusion of the ingredient information had the opposite effect[20]. This was supported by a study where the researchers discovered that non-experts were typically less concerned about nutritional labelling, as it made them feel insecure and confused[17] (Figure 4).

TABLE 2: TESTED ATTRIBUTES IN DISCRETE CHOICE EXPERIMENT. All back label statements were found to have a positive effect on consumer purchase intention except for the ingredient attribute[20].

Attribute	Intention
History	+
Grape Source	+
Production	+
Simple taste	+
Elaborate taste	+
Food pairing	+
Consumption advice	+
Environmental	+
Website	+
Ingredients	-
Price	+

It is also important to note that a study conducted by Escandon-Barboas and Rialp-Criado[22] found that non-experts relied less on nutritional information. They discovered that both the front and back labels were considered equally important from a consumer's point-of-view. They also validated that the back label positively influences purchase decisions when presented in an easy-to-read manner[22]. This result was contrasted by that of Thomas and Pickering[18], who used a questionnaire of ten questions to assess the impact of certain pieces of information on the consumers' purchase intention. The results concluded that non-experts were less likely to carefully read the back-label content[18]. This study noted that the

WINE LABEL REQUIREMENTS IN ONTARIO Any word, phrase, number, or symbol that may mislead the consumer are prohibited. As per the LCBO, the following requirements need to be in a single field of vision: common name, net quantity, alcohol strength and country of origin[21]. Other requirements include an allergen declaration, dealer name and address, barcode, organic claims, and a legible lot code[21].

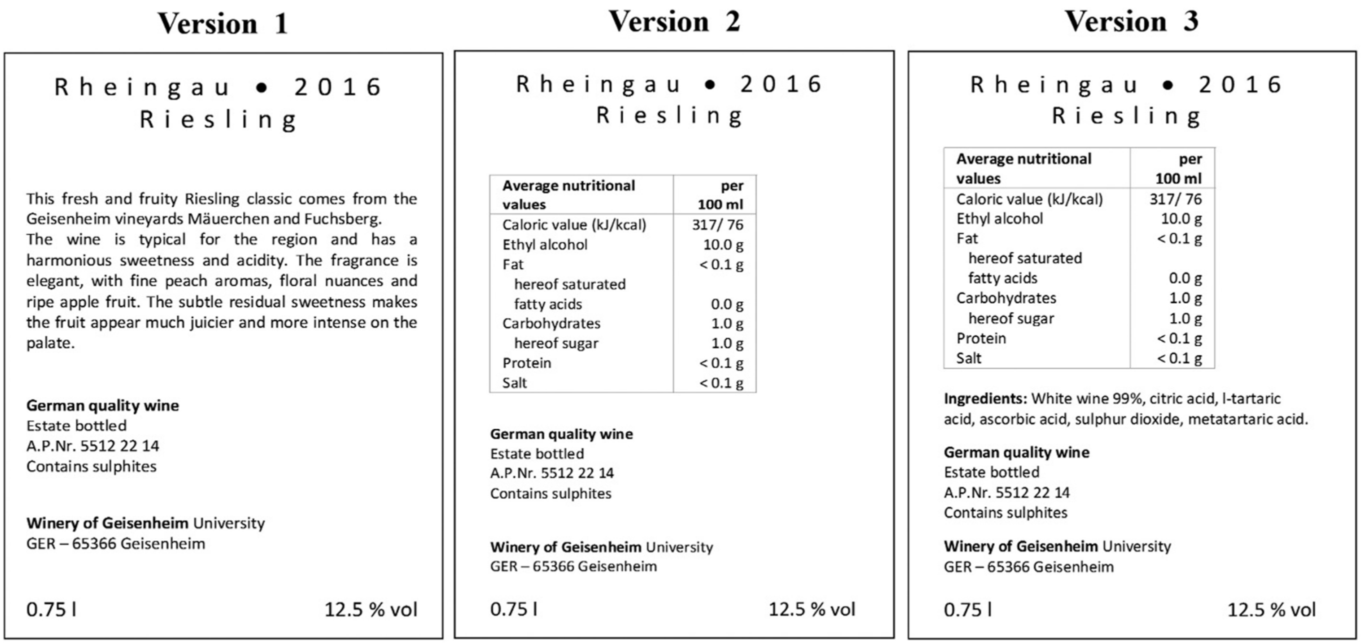

FIGURE 4: SUMMARY OF COMMON SIGNIFIERS ON WINE LABELS. An example of a comparison between detailed versus non-detailed back labels to assess consumer reaction. Version 1 shows all the legally required information as per the European commission, while version 2 includes a detailed nutritional table. Version 2 is a proposed change that can be realistically implemented, while Version 3 is an undesirable design due to the extensive list of information[17].

elements of parentage, endorsements and wine attributes were the most important factors on the back label that influence purchase decisions[18]. Despite the contrasting findings of the studies, they both concluded that back labels should be designed to appeal to newer, less experienced consumers.

There has been growing controversy regarding the accuracy of back-label information. As mentioned earlier, taste is one of the main cues customers look for when reading a wine label. A study conducted by Charters, Lockshin and Unwin[19], demonstrated that in blind taste tests, participants found it difficult to match the taste of wine to its listed description. Although not significantly alarming, it provides wineries with crucial information to more accurately market to non-experts.

All in all, the back label carries immense potential and currently under-appreciated to educate and convince a non-expert consumer to buy a new bottle of wine. Although fewer studies have been done on the back label in comparison to the front, there appears to be a complementary effect. For example, in relation to the front label, simple descriptions of a wine's tastes and smells are often most effective[19]. Researchers have also highlighted the limitations of studying wine labels due to the many external factors which influence the way back labels are perceived. Examples of these factors include, but are not limited to: culture, history, tradition, label regulations and price range all vary from one geographic location to the next[20,23]. Although the back label has been under-utilized, in conjunction with the front label it still holds importance.

Cognitive Dissonance: the state of having inconsistent thoughts, beliefs, or attitudes, especially as relating to behavioral decisions and attitude change.

CONCLUSION

It is evident that there are many considerations a wine marketing team must make to maximize profit. The label is the most important feature in branding a wine because it has been shown to be crucial in determining wine purchasing intentions. Creating a strong brand can ensure that not only is your bottle chosen from the shelf, but that it can be enjoyed and subsequently repurchased. The first impression of the label is incredibly important to the marketability of a wine.

This report highlights the intricacy of marketing wine to consumers. Between the front and back labels, text-based and image-based information and cues, there are many details for a company to consider in order to entice new buyers. The complexity highlights the advantage and importance of continued research in the areas of marketing and semiotics as they relate to wine in the race for companies to be competitive in the already saturated wine market. Making a bottle stand out amongst shelves of competing brands is necessary to ensure success. Knowing and understanding the consumer base can inform decisions about what to include on the bottle. A more mature and knowledgeable audience likely calls for a sophisticated label with key information about ingredients and country of origin while a brand targeting a younger demographic may want to use bright colours, abstract images and information such as recommended food pairings. Wine labels are key in conveying product and brand information, and in influencing the consumer's primary purchase intention. It is clear that text, images, and colour are all important considerations for brands to help get their bottle from the shelf into your cart.

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