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Abstract

Climate change presents risks and opportunities for the wine industry. Little has been written about possible impacts on wine safety. This chapter draws on the latest scientific consensus regarding climate change to examine how changing production environments could be realised in the vineyard and winery. The impacts of climate change are likely to vary between viticultural regions, so this chapter looks at a range of conditions: temperature, precipitation, humidity, variability and extreme weather events which could impact viticulture and wine to differing degrees in different locations. It identifies wine safety risks resulting from climatic conditions directly, and indirect risks from practices employed to manage climatic conditions and weather events. Whilst climatic trends and changes to average conditions can often be managed in the vineyard, the frequency and nature of extreme events may prevent appropriate management strategies being implemented. In the winery a combination of oenological capability and due diligence is required to ensure product quality and safety. These will function best when supported by appropriate legal or regulatory control.

Keywords (separated by “ - ”)

Alcohol - Allergens - Climate change - Fungal disease - Metabolites - Plant protection products - Product safety - Quality assurance - Residues - Vine pest - Viticulture - Winemaking

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Chapter 5
Global Climate Change and Wine Safety

[AU1] **Matteo Marangon, Alistair Nesbitt, and Tony Milanowski**

Abstract Climate change presents risks and opportunities for the wine industry. Little has been written about possible impacts on wine safety. This chapter draws on the latest scientific consensus regarding climate change to examine how changing production environments could be realised in the vineyard and winery. The impacts of climate change are likely to vary between viticultural regions, so this chapter looks at a range of conditions: temperature, precipitation, humidity, variability and extreme weather events which could impact viticulture and wine to differing degrees in different locations. It identifies wine safety risks resulting from climatic conditions directly, and indirect risks from practices employed to manage climatic conditions and weather events. Whilst climatic trends and changes to average conditions can often be managed in the vineyard, the frequency and nature of extreme events may prevent appropriate management strategies being implemented. In the winery a combination of oenological capability and due diligence is required to ensure product quality and safety. These will function best when supported by appropriate legal or regulatory control.

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5.1 Introduction

The role of climate is critical in determining spatial viticultural and varietal suitability (Fraga et al. 2012; Moriondo et al. 2013; Santos et al. 2012) but climate also plays a significant part in the selection of viticultural and oenological practices used to achieve desired grape quality parameters, viable yields and targeted wine styles. Changes to climate conditions could result in changes to management

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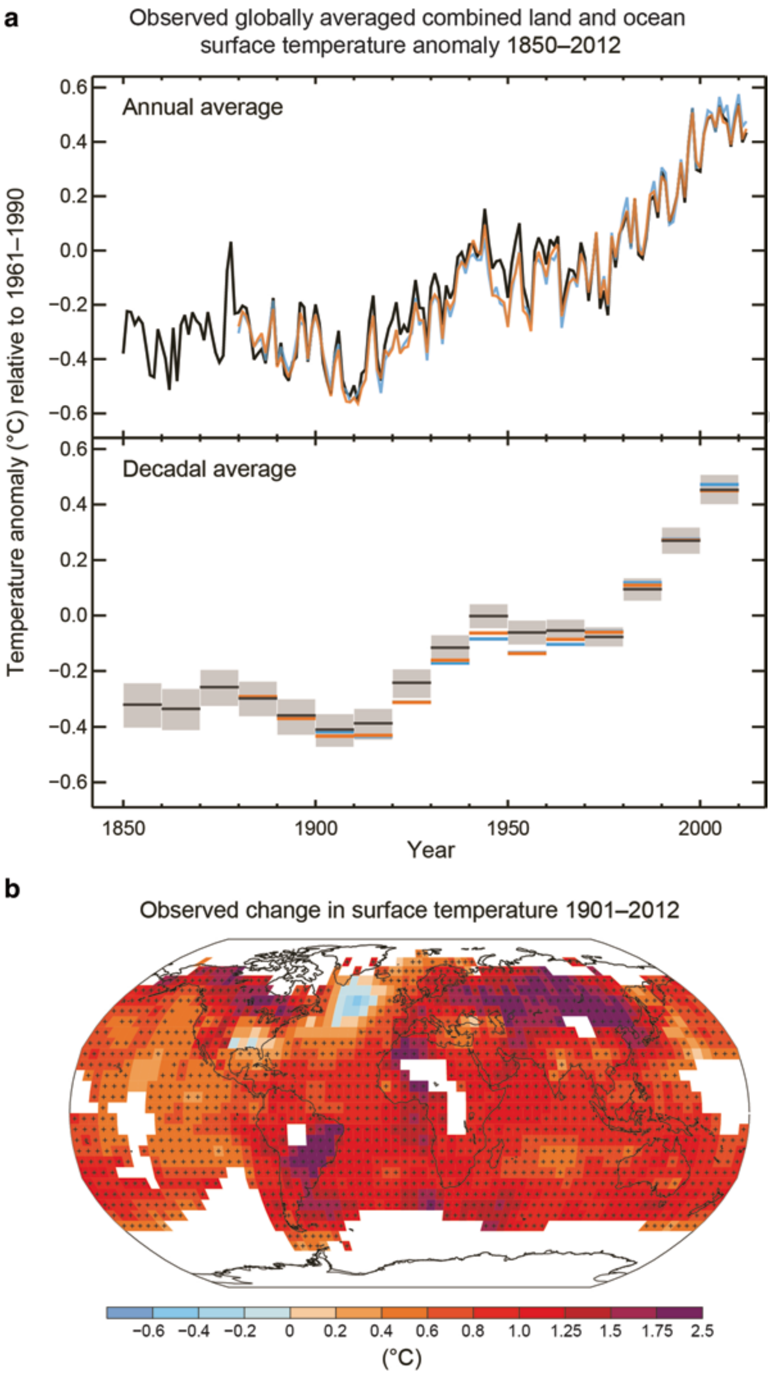
practices in the vineyard and winery that ultimately affect style and quality of wine. Whilst there is the ability within viticulture and oenology to adapt to climate change through various techniques, adaptive capacity is not infinite for any given variety, location or wine style. This chapter addresses the subject of climate change and wine production with a specific focus on wine safety, an issue that is important to producers and consumers. It includes a review of how climate change may impact viticultural and oenological activities, which in turn, without appropriate management, could affect wine safety. In doing so, potential health and safety risks and recommended strategies to manage those risks are outlined.

5.2 Climate Change

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. The IPCC has concluded that warming of the world's climate system is unequivocal, with globally averaged combined land and ocean surface temperature data, calculated by a linear trend, showing a warming of 0.85 °C (0.65–1.06 °C) over the period 1880–2012 (IPCC 2013). The last three decades have been successively warmer than any preceding decade since 1850 (Fig. 5.1a) and between 1901 and 2012, the longest period when calculation of regional trends is sufficiently complete, almost the entire globe experienced surface warming (Fig. 5.1b). Although there is less confidence about changes to precipitation at a global scale, since 1951 precipitation has increased when averaged over the midlatitude land areas of the Northern Hemisphere and the frequency or intensity of heavy precipitation events has likely increased in North America and Europe (IPCC 2013). Changes in extreme weather and climate events have also been observed since about 1950. It is very likely that (1) the number of cold days and nights has decreased; (2) the number of warm days and nights has increased; (3) the frequency of heat waves in large parts of Europe, Asia and Australia has increased and (4) there are likely more land regions where the number of heavy precipitation events has increased than where it has decreased (IPCC 2013).

Human influence has been detected in warming of the atmosphere and ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise and in changes in some climate extremes (IPCC 2013). The IPCC

Fig. 5.1 (**a**) Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three data sets. *Top panel*: Annual mean values. *Bottom panel*: Decadal mean values including the estimate of uncertainty for one dataset (*black*). Anomalies are relative to the mean of 1961–1990. (**b**) Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one data set (*orange line* in panel **a**). Trends have been calculated where data availability permits a robust estimate (i.e. only for *grid boxes* with greater than 70 % complete records and more than 20 % data availability in the first and last 10 % of the time period). Other areas are *white. Grid boxes* where the trend is significant at the 10 % level are indicated by a + sign (IPCC 2013)


a
Observed globally averaged combined land and ocean surface temperature anomaly 1850–2012
Annual average
Decadal average
Temperature anomaly (°C) relative to 1961–1990
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
1850
1900
1950
2000
Year
b
Observed change in surface temperature 1901–2012
−0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1.0 1.25 1.5 1.75 2.5
(°C)

concluded that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-twentieth century. Whilst the causes of climate change are not discussed further in this chapter it is important to note that climate change mitigation practices can be employed by the wine production sector, particularly through energy efficiency, more environmentally sustainable packaging and more efficient distribution methods.

The IPCC uses a series of greenhouse gas representative concentration pathways (RCP) to illustrate future climate conditions. The pathways describe four possible climate futures, which depend on the concentration of greenhouse gases emitted in the future. RCP2.6, RCP4.5, RCP6.0 and RCP8.5 are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0 and +8.5 W/m^2, respectively). Global surface temperature change for the end of the twenty-first century is likely to exceed 1.5 °C relative to 1850–1900 for all RCP scenarios except RCP2.6 (Fig. 5.2). Natural internal variability will continue to be a major influence on climate, particularly in the near-term and at the regional scale but inter-annual and decadal variability is unlikely to be regionally uniform (IPCC 2013).

The IPCC (2013) predicts that the contrast in precipitation between wet and dry regions and seasons will increase, although there may be regional exceptions. The high latitudes and the equatorial Pacific Ocean are likely to experience an increase in annual mean precipitation by the end of this century under the RCP8.5 scenario. In many midlatitude and subtropical dry regions, mean precipitation will likely decrease, while in many midlatitude wet regions, mean precipitation will likely increase by the end of this century under the RCP8.5 scenario (Fig. 5.3).

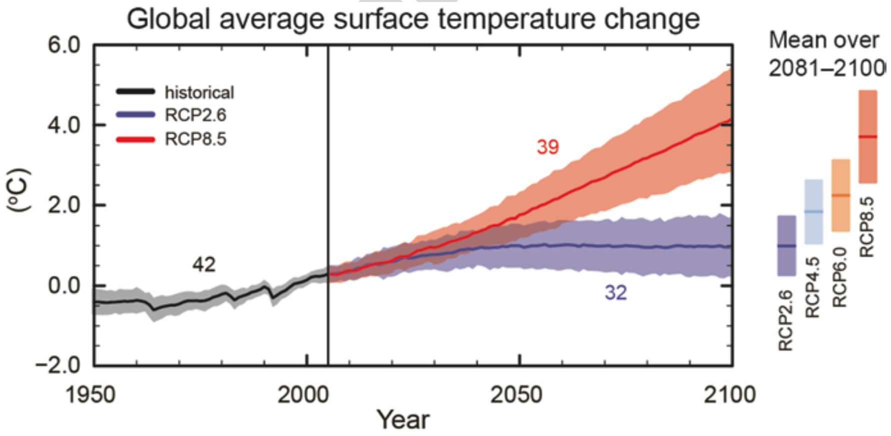


Fig. 5.2 Multi-model (CMIP5) simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986–2005. Time series of projections and a measure of uncertainty (*shading*) are shown for scenarios RCP2.6 (*blue*) and RCP8.5 (*red*). *Black* (*grey shading*) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as *coloured vertical bars*. The numbers of CMIP5 models used to calculate the multi-model mean are indicated (IPCC 2013)

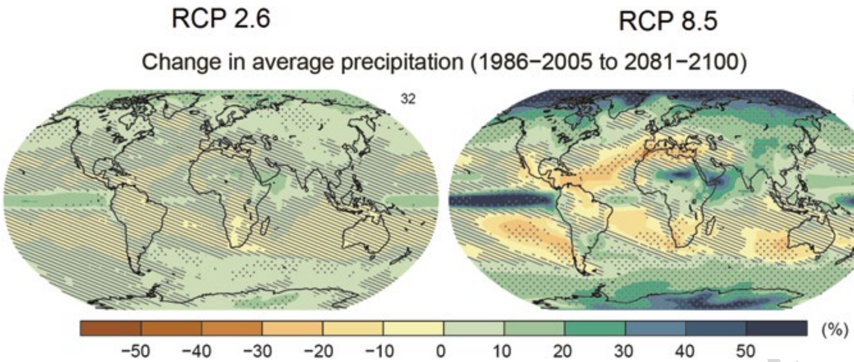


Fig. 5.3 Maps of CMIP5 multi-model mean results for the scenarios RCP2.6 and RCP8.5 in 2081–2100 of average percent change in annual mean precipitation. Changes are shown relative to 1986–2005. The number of CMIP5 models used to calculate the multi-model mean is indicated in the *upper right corner* of each *panel. Hatching* indicates regions where the multi-model mean is small compared to natural internal variability (i.e. less than one standard deviation of natural internal variability in 20-year means). *Stippling* indicates regions where the multi-model mean is large compared to natural internal variability (i.e. greater than two standard deviations of natural internal variability in 20-year means) and where at least 90 % of models agree on the sign of change (IPCC 2013)

It is likely that the frequency and duration of warm spells and heat waves, as well as the frequency and intensity of heavy precipitation events, and the intensity and/or duration of drought will increase at a regional or global scale by the end of the twenty-first century.

5.3 Impact of Climate Change on Viticulture and Oenology

Grapes are very sensitive to climate and are predominantly grown in narrow latitudinal bands (30–50°N and 30–40°S) and in specific climatic conditions, characterised by a lack of extreme heat and extreme cold (Schultz and Jones 2010; White et al. 2006). Climate change will have particular significance for grape production where changes or climate-related events occur during the grape-growing season (April–October in the Northern Hemisphere, October–April in the Southern Hemisphere). Increasing temperature trends, a greater frequency of extreme weather, variability, altering precipitation and evapotranspiration trends all have the potential to impact grape production at annual or longer term time scales (Waters et al. 2005).

Warming conditions will provide potential for new wine-producing regions and will likely lead to a further increase in average growing-season temperatures in existing regions. Recent warming trends and phenological shifts have been found in many wine production regions including Australia, the USA, Canada, New Zealand, South Africa and Europe (Hannah et al. 2013; Jones and Alves 2012; Mira de Orduña 2010). The increase in average temperature during the growing season will impact some key physiological processes, potentially affecting grape berry composition and vineyard productivity.

In addition to changes in average growing-season temperatures, acute weather events such as extreme heat or intense precipitation, and chronic longer term events such as heat waves, drought or prolonged periods of precipitation, will also likely affect grape and wine production above and beyond the impact of conditions that contribute to typical vintage variation. Some existing viticultural regions have already suffered from extreme events, e.g. droughts in South East Australia affecting areas like the Murray Darling Basin, bushfires in Victoria (Australia) leading to smoke taint risk, flooding in the Orange River (South Africa) wine region in 2011 and flooding and hail in central European wine regions in 2013.

These changes and conditions will not affect all production regions uniformly and will likely concern some more than others; indeed rising average temperatures may present opportunities for new production regions. In this chapter the effects of climate conditions on vines and wines are explored because the management of climate and weather events is critical to ensuring production viability, and to safeguarding against potential knock-on effects that could impact wine safety. Particularly, in subsequent sections, findings related to the impact of main climate changes (temperature increase, precipitation and humidity changes and extreme events) are presented as focussed on viticulture, winemaking and wine safety effects.

5.4 Impact of Temperature Increase

In the context of a warming climate, plant development is mainly affected by driving variables such as temperature, solar radiation changes and CO_2 content (Bindi et al. 1996). Longer and warmer growing seasons with increased average temperatures directly affect the rate at which physiological processes such as photosynthesis and respiration occur in plants (Keller 2010a), and therefore have the potential to increase berry sugar content and pH, lower total acidity, anthocyanin and methoxypyrazine levels (Keller 2010b; Mira de Orduña 2010), and cause modifications to the content of other compounds that could have technological impacts, such as protein levels (Waters et al. 2005).

5.4.1 Effects of Temperature Increase on Viticulture

Grapevines (*Vitis vinifera*) are characterised by a distinct phenological cycle (bud break, flowering, berry growth, veraison, maturation, leaf fall and dormancy) that is predominantly regulated by changes in thermal conditions (Iland et al. 2011). The period between budburst and harvest has advanced and become shorter in some regions and earlier flowering, veraison, ripening and harvests have also been related to warming temperatures (Duchêne and Schneider 2005; Keller 2010c).

Research conducted in France found that the phenology of grapes had significantly advanced over a 50-year period with harvest now almost a month earlier (Seguin and de Cortazar 2005). These phenological shifts are likely to cause climatic-related challenges.

Temperature is a major source of seasonal and regional variation in fruit quality traits with direct consequences for wines. Indirectly, the notion that higher temperatures during the growing season yields juice with higher sugar content, higher pH and lower total acidity is well established (Iland et al. 2011; Keller 2010b). It has been recently demonstrated that the effect of temperature on pH and total acidity is varietal specific (Sadras et al. 2013).

Sugar accumulation is directly affected by temperature either via an increase in photosynthetic efficiency during the ripening season especially in cool climates or by indirect sugar concentration due to berry dehydration particularly in warm climates (Keller 2010a).

Increased temperatures also affect grape organic acid content (Iland et al. 2011). The main organic acid in grapes, tartaric acid, is relatively stable during the ripening process (Melino et al. 2009), while the opposite is true for the second most represented grape acid: malic acid (Mira de Orduña 2010; Sweetman et al. 2009). The decrease in tartaric acid concentration during ripening is mostly due to dilution associated with the increase in berry volume. In pre-veraison malate accumulation is at a maximum between 20 and 25 °C, and decreases at higher temperatures (Keller 2010b). Therefore hot condition pre-veraison, typical of warm growing regions, can significantly impact the accumulation of malate and negatively affect final juice acidity. Post-veraison, the metabolism of sugar starts favouring glucose and fructose accumulation and synthesis rather than catabolism. Hence sugars stop being the major source of carbon for plant growth and are replaced by malic acid, with its content decreasing over time (Sweetman et al. 2009).

Temperature also plays a role in modulating the final content of other compounds in berries essential in determining grape quality, such as phenolics, flavour compounds and proteins. In general higher temperatures lead to riper grapes in which fruity flavours tend to be predominant, rather than the green flavours associated with methoxypyrazine (Harris et al. 2012). Proteins are constitutively produced by the plant during ripening and their concentration is linearly correlated with berry sugar concentration (Pocock et al. 2000).

Global warming has been associated with the migration of diseases poleward at a speed of 2.7 ± 0.8 km/year since 1960 (Bebber et al. 2013). This trend has been observed for several pathogens and vectors affecting vineyards. Increasing temperatures in Europe may increase susceptibility to the European grapevine moth and powdery mildew (Caffarra et al. 2012). Other pests, whose distribution can be considered in part humidity and temperature driven, include the glassy winged sharpshooter which brought Pierce's disease to California, mealy bugs, grass grubs, erinose mites and the Asian lady beetle (Mozell and Thach 2014). Predictions for an important grapevine fungal disease, *Botrytis cinerea*, are unclear. Some authors affirm that high temperatures (>35 °C) could have beneficial effects in protecting plants from several diseases including *Botrytis cinerea*. However, hot conditions associated with high radiation levels are likely to damage grapes due to sunburn, potentially enabling *Botrytis cinerea* infections later in the season (Steel and Greer 2008). Whilst this list is by no means exhaustive it illustrates potential pest problems associated with changing temperature regimes.

5.4.2 *Effects of Temperature Increase on Winemaking*

Under increased growing-season temperatures grapes have the potential to reach maturity quicker. In this context, winemakers are faced with several oenological challenges because producing high-quality wines from grapes with increased sugar levels and lower acidity can seriously affect the production process. High sugar must is problematic as glucose and fructose are primarily metabolised into ethanol, carbon dioxide and heat, and the resulting elevated ethanol levels interfere with different aspects of yeast metabolism, including cellular transport of glucose, ammonium and amino acids (Leão and van Uden 1982; Leão and van Uden 1984; Leão and Van Uden 1983). High alcohol content can also affect yeast cell fluidity, disrupt plasma membranes and cause cellular damage and cell death (Kubota et al. 2004). In parallel wine accumulates acetyl aldehyde as a result of yeast metabolism, at the same time as ethanol, that can have negative toxic effects on yeast (Bisson 1999). Ultimately high alcohol levels alone, or combined with other stress conditions such as elevated ferment temperatures, low nutrition or the presence of inhibitory compounds like medium-chain fatty acids, can result in fermentations ceasing prematurely (Bell and Henschke 2005). This can lead to the production of wines with residual sugar that in turn are responsible for non-conformance to a desired style and may risk microbial spoilage, from yeasts and bacteria.

When faced with high sugar must winemakers can look to either (1) manage the fermentation process with the aim of producing a high-ethanol wine or (2) reduce the final alcohol concentration. The fermentation process can be better managed by using ethanol-tolerant yeast strains. Yeast ethanol tolerance can also be improved by the presence of sterols, which improve cell membrane fluidity. Sterols can be added by oenological adjuvants, or their production induced by the incorporation of small amounts of air during fermentation. Low-temperature fermentation (<25 °C) can also mitigate the negative impact of high ethanol levels on yeast health (Bauer and Pretorius 2000).

Alcohol reduction can be difficult to achieve in wine. Legal restrictions mean that dilution of initial sugar levels is problematic and generally the addition of water is only allowed when used to prepare oenological additives such as yeast and fining agents. Legal exceptions in some areas do allow the incorporation of water (California) or water-derived from grape concentration processes (Australia).

Ethanol reduction can also be achieved biologically. While ethanol is the primary product of *Saccharomyces* yeast metabolism, yeast can also convert carbohydrates to glycerol, pyruvic acid and other metabolites (Kutyna et al. 2012). There has been considerable research into decreasing ethanol production in favour of the production of glycerol using genetic modification (Varela et al. 2012), directed breeding techniques and adaptive evolution approaches (Kutyna et al. 2012; Tilloy et al. 2014). Although future yeast strains may provide a means of minimising ethanol production (Varela et al. 2012), to date efforts in producing such strains have been unsatisfactory because of diverse problems including the accumulation of high levels of spoilage compounds such as acetic acid (Cordente et al. 2013). Also widespread moratoriums on the use of genetically modified organisms by many wine-producing countries limit the potential for development of customised yeast strains (Borneman et al. 2013).

Ethanol levels can be reduced by winemaking activities during and post-fermentation. With vigorous production of carbon dioxide, the gas flux can entrain ethanol and cause it to be lost to atmosphere (Boulton et al. 1995; Zimmermann et al. 1964). Furthermore, storage of barrels in >70 % relative humidity environment can cause the preferential evaporation of ethanol over water, resulting in a decrease in final alcohol levels (Boulton et al. 1995). Winemakers can also attempt to lower the alcohol content by processes such as nano-filtration, osmosis, osmotic distillation, pervaporation and low-pressure Spinning Cone™ columns (Schmidtke et al. 2012). However, the uptake of this technology by the industry is limited by legal restriction in some areas, and by their costs and potential sensory implications.

At the same time as increasing sugar levels, acid levels decrease and wine pH increases. Acidity is important for organoleptic reasons because it provides freshness and balance to wine and influences the colour of red wines (Peynaud 1984). It also plays a role in ensuring that wine is less susceptible to oxidation as the extent of polyphenol oxidation decreases at a lower pH (Singleton 1987). Low pH also reduces the risk of microbial spoilage as some spoilage microorganisms, like *Lactobacillus* and *Pediococcus* strains which are unable to grow in wine at a pH below 3.5 (Davis et al. 1986). Finally, the proportion of molecular sulphur dioxide increases at decreasing pH levels, meaning that sulphites are more effective in controlling spoilage (Zoecklein et al. 1995). For all these reasons, acidity and pH are crucial parameters to control.

Wine regions which routinely suffer from musts with high pH and low acidity can often legally acidify wine through tartaric acid additions. Areas with more marginal climates can request a legal dispensation in certain vintage conditions to allow acidification; however this process can be lengthy and authorisation for acidification may be delayed (EC 2008). With climate change this process may require revisions to enable increased or speedier acidification of wines in difficult years.

Acidification methods that do not require addition of acids are also used by winemakers. These include the amelioration of high pH musts with either additions of unripe fruit or blending with varieties naturally high in acidity. Other methods include the preservation of wine acidity by avoidance of malolactic fermentation that reduces malic acid to the relatively weaker lactic acid (Ribéreau-Gayon et al. 2006), or using yeast strains to produce high levels of acids (succinic and lactic) during fermentation as a way of increasing acidity (Su et al. 2014). An alternative to increasing acidity is to mitigate the possible negative effects of both oxidative and spoilage risk of high pH through the use of reductive handling techniques, such as inert gas blanketing and sparging, or through increasing sulphite levels (Oliveira et al. 2011).

Grapes at increased maturity will exhibit higher levels of proteins, anthocyanins and polyphenols. During the winemaking process these may be extracted to higher than desired levels, effecting wine style and organoleptic character. Winemakers may need to modify processes such as skin maceration, grape pressing or temperature to modulate the extraction levels. Alternatively they can look to remove excessive levels of these compounds through the use of fining agents (bentonite, gelatin, ovalbumin or wheat) (Maury et al. 2003; Pocock et al. 2011). These operations can impact the final quality and safety of wines in different ways.

5.4.3 Effects of Temperature Increase on Product Safety

One of the wine safety concerns associated with increased ripeness is increased sugar and consequently higher alcohol levels. Harmful consumption of alcohol has been highlighted by the World Health Organisation (WHO) as having a significant impact on human health with approximately 5 % of total world deaths and diseases attributable to harmful use of alcohol (World Health Organisation 2010). A recent global alcohol strategy targets a 10 % reduction in harmful alcohol use by 2025 (World Health Organization 2014) and one means of achieving this aim is to reduce alcohol content in alcoholic drinks, including wine (World Health Organization 2010). As a consequence, potential increasing wine alcohol content, caused by a changing climate, is in conflict with the WHO aims.

Wines that are susceptible to microbiological spoilage because of their high pH and low levels of molecular sulphite are a potential wine safety risk. When spoilage occurs in a wine, unknown microorganism can grow, thus producing metabolites that can represent a safety concern. Major risks include the potential for lactic acid bacteria to produce biogenic amines such histamine, tyramine and putrescine in sufficient quantities to cause concerns for vulnerable consumers (Landete et al. 2007). In addition, some microorganisms use amino acids such as arginine in their metabolism producing high levels of urea and citrulline, which in turn reacts with ethanol to form ethyl carbamate which is classified as a probable human carcinogen (IARC 2010; Mira de Orduña et al. 2000).

As way of combatting an increased risk of microbial spoilage, winemakers may be forced to employ higher levels of sulphite to protect wines. However sulphites are a known wine safety concern and total levels allowed are regulated by all wine-producing countries (OIV 2014). The WHO found that in countries with significant wine consumption patterns, wine can be a major contributor to the total dietary sulphite intake and may cause recommended adult daily intake of 0.7 mg/kg body mass to be exceeded (FAO/WHO 2009).

The process of increased wine fining can also cause wine safety concerns. Some proteinaceous fining agents may persist in wine after use and can cause allergic reaction in consumers. Studies have shown the potential for gluten, milk, egg and fish material to remain in the wine and result in positive enzyme-linked immunosorbent assay (ELISA) or skin-prick testing (Vassilopoulou et al. 2011). To minimise safety concerns for at-risk consumers, winemakers can adopt different strategies: (1) quantify potential allergen residues, (2) reduce quantities via bentonite fining or filtration (3) or label wines with appropriate warning guidelines (Deckwart et al. 2014). While labelling for potential allergens is required in many locations, including the EU, Australia and New Zealand, increasing fining agent residues poses potential risks in countries where additions are not strictly regulated (Deckwart et al. 2014).

Riper grapes have also higher quantities of unstable proteins that need to be removed through bentonite additions (Waters et al. 2005). Under climate change conditions there are two potential risks. Higher protein content may require a higher degree of bentonite fining to remove them, a process that can alter the metal ion content in wines with potential increase of the aluminium, iron and arsenic levels leading to potential health or legal concerns (Catarino et al. 2008; Tariba 2011). The second risk is that some wine proteins are known allergens including endochitinase, lipid transfer proteins and thaumatin-like proteins (Marangon et al. 2009) that have the potential to cause allergic reactions in some consumers (Pastorello et al. 2003).

5.5 Impact of Precipitation and Humidity Changes

In some regions periods of drought and water stress may become more common under climate change conditions, thus increasing the need for irrigation where able. Conversely, other regions could see an increase in rainfall or in extreme precipitation events, with possible consequences such as increases in erosion, changes in the spatial distribution of pests and diseases that affect grapes and vines and increases in disease pressures, particularly associated with warmer conditions (Chakraborty et al. 2000).

5.5.1 Effects of Precipitation and Humidity Changes on Viticulture

The extent and distribution of precipitation over the vegetative period are critical to viticulture, as water stress and excessive humidity can lead to a wide range of positive or negative effects (Austin and Bondari 1988). Whilst a critical reduction in water availability for vines can be managed through irrigation, the costs and required water availability can make irrigation unviable. Reduced water availability during the growing season can have different effects at different phenological stages, causing poor shoot growth, low leaf area and hence limited photosynthesis, poor flower cluster development, flower abortion and poor berry fruit set (Fraga et al. 2012, 2013; Iland et al. 2011). On the other hand, excessive precipitation and humidity, particularly during the early stages of development, can promote excessive vegetative growth, resulting in denser canopies and a higher likelihood of disease problems (Fraga et al. 2012), as well as sugar dilution and delayed berry ripening (Fraga et al. 2013).

Given that changing climatic conditions may alter the frequency, intensity, distribution and type of pests and diseases present in vineyards, viticulturists will be faced with a dynamic pest population environment and therefore will need suitable pest control strategies that they can apply readily. Preventing the spread of diseases through additional applications of plant protection products could increase costs (economical and environmental) and risks, including those to humans caused by residues and toxins.

5.5.2 Effects of Precipitation and Humidity Changes on Winemaking

With changing precipitation and humidity levels in vineyards there is the risk of increased occurrence of fungal diseases such as *Botrytis cinerea* (grey rot), *Aspergillus* spp., *Plasmopara viticola* (downy mildew) and *Erysiphe necator* (powdery mildew) (Barata et al. 2012). These diseases and the direct effects of heavy [AU24] precipitation or hail (referred to in Sect. 5.5.3) can damage berry skin integrity, leading to an increased risk of microbial spoilage in wines (Barata et al. 2012). Damaged fruit requires extra care in the winery to minimise possible quality losses from accelerated oxidation or organoleptic taints such as mouldy and earthy attributes (Steel et al. 2013). One option is to remove diseased fruit before it enters the winery, by harvest selection or sorting (Evans 2013). If grapes cannot be sorted prior to processing then winemakers need to try to minimise the impact of fungal contamination by increasing the use of sulphites, minimising the exposure of must to oxygen, using gentler processing techniques, minimising the contact between grape juice and solids and using fining agents (Steel et al. 2013).

An increase in the use of plant protection products to mitigate or minimise the risk of infection in the vineyard comes with the risk of inappropriate use (e.g. too high rates, too close to harvest date) that can leave residual spray on the fruit (Vaquero-Fernández et al. 2013) which may be problematic during the wine production process.

5.5.3 Effects of Precipitation and Humidity Changes on Product Safety

Fungal-contaminated grapes can contain mycotoxins such as ochratoxin A (OTA), a nephrotoxic, teratogenic and immunotoxic fungal metabolite found in many food and beverage products including wine (Shephard et al. 2003). Ochratoxin A (OTA) is classified as possible human carcinogen by the International Agency for Research on Cancer (IARC 1993), and its occurrence is predominantly associated with contamination by *Aspergillus carbonarius* and to a lesser extent *Aspergillus niger*, *Aspergillus aculeatus* and *Aspergillus tubingensis* (Medina et al. 2005). The incidence of OTA in wines is related to climatic conditions. In warm growing regions like Southern Europe and South Africa, OTA is the principal mycotoxin found in wines, and its occurrence is related to the presence of *Aspergillus* species (Anli and Bayram 2009), while wines from cooler regions can also contain OTA, but the fungi responsible are likely from the *Penicillium* species (Battilani et al. 2003; Varga and Kozakiewicz 2006). In the first resolution of 2005, the International Organisation for Vine and Wine (OIV) indicated that processing fruit gently and minimising extraction from grape solids are the best practices to reduce OTA in wines (OIV 2005). In addition, removal of skins and racking reduces the risk of fungal contaminants, particularly when coupled with the use of yeast hulls and fining agents such as activated charcoal (OIV 2005; Del Prete et al. 2007). Some strains of lactic acid bacteria have also been shown to reduce OTA contamination, and these species should be used in preferential inoculum of wines undergoing malolactic fermentation (Del Prete et al. 2007; Shetty and Jespersen 2006).

Another mycotoxin, aflatoxin B1 from *Aspergillus flavus*, one of the most carcinogenic natural materials, has been detected in vineyards (Inoue et al. 2013; El Khoury et al. 2008) and represents a risk to winemaking because if it is present in high levels in grapes it can be transferred to the resulting must (El Khoury et al. 2008). The content of aflatoxin B1 is reduced during fermentation through the action of yeast adsorption, but further steps similar to the precautions taken for OTA may also be employed (Csutorás et al. 2014; Inoue et al. 2013).

Residual plant protection products found on harvested grapes can affect fermentation and other biochemical process, depending on specific residue types and species of microbiota present (Caboni and Cabras 2010; Calhelha et al. 2006). They also have the potential to persist in the winemaking process if not properly managed, and can be detected in finished wines (Pesticide Action Network Europe 2008). As plant protection products include a diverse range of functional chemicals including heavy metals (Tariba 2011), their removal in winemaking needs to include strategies that target different compounds. For instance, residues of fenamidone, pyraclostrobin and trifloxystrobin can be adsorbed by wine solids such as grape skins and yeast lees that can subsequently be removed through racking (Garau et al. 2009). Other products such as valifenalate, iprovalicarb, fenhexamid, metalaxyl and procymidone are more persistent and leave greater residues in wines (Čuš et al. 2010; González-Rodríguez et al. 2011). More persistent products can be removed or reduced through additional steps such as (1) employing carbonic maceration techniques to reduce cyprodinil (Fernández et al. 2005); (2) fining with activated charcoal and casein to reduce agents such as fludioxonil, pyrimethanil, penconazole, imazalil and tetradifon (Sen et al. 2012) and (3) fining with bentonite to remove carbendazim (Ruediger et al. 2004).

5.6 Impact of Climatic Variability and Extreme Events

Climate change may result in increasing variability and extreme events in some areas. Seasonal variability can be attributable to an increased occurrence of extreme events such as unusual periods of high temperatures, heavy storms, hail, frost drought and bushfires (Mira de Orduña 2010; Olesen and Bindi 2002).

5.6.1 *Effects of Climatic Variability and Extreme Events on Viticulture*

Heavy precipitation and hail can have devastating effects on the current season's crop and on the following years' harvest. They can cause severe plant defoliation before adequate reserves have been accumulated, thus negatively impacting development the following spring, and leading to a decrease in bud fruitfulness and production (Iland et al. 2011; Olesen and Bindi 2002).

Cool-climate wine-producing regions are particularly exposed to the risk of early frost events due to the advancement of budburst, driven by increased air temperature in the spring period (Molitor et al. 2014). Frost events can limit the fruitfulness and yield of vines as frost-damaged shoots originating from the primary buds are replaced by secondary buds that are less fruitful (Iland et al. 2011). Several methods to protect vines from frost are being trialled or are available, including hydrophobic particle films and acrylic polymers (Fuller et al. 2003), application of plant growth regulators and oils to delay budbreak and the use of sprinklers, wind machines, heaters, helicopters and several chemical sprays (Poling 2008).

Extended periods of high temperatures, possibly accompanied by drought, can result in severe vine damage due to water stress, protein denaturation caused by extreme heat, damage to plant tissues and in extreme situations bushfires. This latter issue has been observed, more recently so, in several wine-growing regions: Australia, California, British Columbia, Southern Europe and South America. Bushfires not only impact the ecology of environments and the safety of populations, but have the potential to damage vines and vineyard infrastructures (Scarlett et al. 2011). By looking at the effect of smoke on the physiology of grapevine leaves, Bell et al. (2013) reported that for most varieties, short-term exposure to smoke had no effect, or a transient effect, on leaf physiology. All varieties examined recovered to pre-smoke functioning within 48 h. Major damage to plants is associated with a level of heat at which severe defoliation occurs (Scarlett et al. 2011). In turn defoliation could have negative effects on yield, floral initiation and accumulation of plant reserves (Iland et al. 2011). Grapevines exposed to smoke during sensitive periods of growth produce wines that can contain smoke-related aromas and flavours making them unpalatable. This most likely causes a decline in product quality and potential financial losses (Mayr et al. 2014).

5.6.2 *Effects of Climatic Variability and Extreme Events on Winemaking*

Climatic variability and extreme events may predominantly influence yields, but will also necessitate winemaking adaptation. In particular, winemakers will have to deal with grapes with undesired levels of key parameters such as ripeness, acidity and flavour profiles as discussed previously. In the case of smoke-tainted grapes, winemakers need to adapt their processing to avoid extraction of volatile phenols and guaiacol glycoconjugates), in the main by reducing skin contact time (Kelly et al. 2014).

5.6.3 *Effects of Climatic Variability and Extreme Events on Product Safety*

The potential safety concerns associated with changes in grape composition and residuals caused by extreme events and climatic variability are similar to those highlighted in the previous sections. Notably, winemakers will need to be vigilant against rising alcohol levels, the formation or introduction of dangerous metabolites and the occurrence of wine spoilage. Winemakers will also have to manage potential residues from fining agents, metals or incorrect employment of plant protection products. Steps outlined previously will need to be employed to ensure production of safe and high-quality products.

5.7 Conclusions

The relationship between climate change and wine production is complex and not uniform across different wine-producing regions. In this context, the experiences and knowledge of any given region can often assist in managing 'new' situations in another. Vineyard managers and winemakers are familiar with managing some degree of climatic or weather variability, usually represented through vintage variation. Where conditions exceed these accepted 'norms' of variance, additional management practices may need to be employed to ensure product quality, consistency and safety. Variability and extreme conditions in some respects present greater threats than changing averages as their acute nature places producers in unfamiliar conditions that they must quickly adapt to and manage.

This chapter has identified three core aspects of climate change that are likely to affect viticulture presently and under future scenarios: temperature, precipitation and extreme events. The extent of changes will vary between regions, temporally and under different RCP scenarios. Many of the potential viticultural impacts identified in literature relate more to issues of yield, wine style and commercial viability than to wine safety.

Key wine safety risks identified in this chapter include high-potential alcohol levels caused by increasing or extreme temperatures; toxic metabolites including biogenic amines formed through wine spoilage as an indirect result of climatic conditions and increased sulphite levels added to prevent spoilage. Viticultural and winemaking activities employed to cope with climatic conditions can also lead to the increased presence of residues. These can be from practices such as plant protection product applications and/or the use of fining materials that potentially introduce allergens.

All of these risks can be managed through production processes critical to ensuring that desirable and safe products are produced. However, the ability of these processes to be implemented and adhered to in all wine-producing and prospective wine-producing regions remains uncertain and consequently a possible source of risk. In both existing and emerging regions there is a need for adequate guidance, regulation and legislation to ensure that management practices, employed under specific climatic conditions, are legal and result in a product that is safe. Having in place adequate quality assurance processes in conjunction with appropriate monitoring by stakeholders should mean that wine products can be produced under climate change conditions without the risk to product or consumer safety, as long as conditions allow sustainable business viability.

Above all, due diligence and product quality assurance are increasingly important in protecting consumer safety. Under climate change conditions knowledge transfer, viticultural and oenological expertise and the ability to quickly adapt to manage different situations are critical to product viability and safety. What is possibly harder to ensure is the maintenance of a given wine style or organoleptic character.

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Queries	Details Required	Author’s Response
AU1	Author “Matteo Marangon” has been treated as the corresponding author. Please check.	
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