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The impact of climate change on the global wine industry: Challenges & solutions

Michelle Renée Mozell, Liz Thach*

Sonoma State University Wine Business Institute, 1801 E. Cotati Blvd, Rohnert Park, CA 94928, USA

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Abstract

This paper explores the impact of climate change upon the global production of winegrapes and wine. It includes a review of the literature on the cause and effects of climate change, as well as illustrations of the specific challenges global warming may bring to the production of winegrapes and wine. More importantly, this paper provides some practical solutions that industry professionals can take to mitigate and adapt to the coming change in both vineyards and wineries.

Keywords: Climate change; Global warming; Vineyards; Wineries; Policies

1. Introduction

Climate and weather have been critical to the story of human development. From the continuous movement of nomadic tribes seeking seasonal feed for their animals to the establishment of agriculturally based civilizations of Egypt, Mesopotamia and China, early humans were dependent upon the benefit and limitations of climate to establish roots and survive (Jones and Webb, 2010). However with the advent of the Industrial Age and the growing dependence upon fossil fuels, the widespread elimination of forests, and the expansive use of agrochemicals, there has been a slow, but steady, shift of the earth's average temperature upward, a phenomenon known as "global warming" (Burney et al., 2013; Jones and Webb, 2010; National Geographic, 2013; Venkataramanan, 2011; IPPC, 2013a).

Though there are some who do not believe humans have an influence upon global climate change, a commanding percentage of scientists have evidence to prove otherwise (IPPC, 2013a). In the past two decades, through private and government-sponsored initiatives, the world community is calling for increased attention to the worsening climate crisis (Iglesias et al., 2012; Schultz, 2010; IPPC, 2013a).

Though wine is not essential to human survival, wine is an important product of human ingenuity. All agricultural activity is decidedly dependent upon and inherently interconnected to climate and weather; grapes are no different. Though grapes are grown worldwide, premium winegrape production occurs within very narrow climate ranges. "Individual winegrape varieties have even narrower climate ranges…for optimum quality and production putting the cultivation of winegrapes at greater risk from both short-term climate variability and long-term climate changes than other crops (Jones and Webb, 2010)." Any shift in climate and weather patterns may potentially affect the wine industry. As a constant companion of human development and an important component of human economic activity, winegrapes, as an agricultural product, and wine (especially premium wine), as an economic commodity, are both at risk due to climate change.

Therefore the purpose of this paper is to explore the impact of climate change upon the global production of winegrapes and wine. It will begin with a review of the literature, including an examination of the cause and effects of climate change, as

*Corresponding author.
E-mail addresses: mmozell@cox.net (M.R. Mozell), Liz@Lizthach.Com, Liz.Thach@sonoma.edu (L. Thach).
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well as illustrations of the specific challenges climate change could bring to the production of winegrapes and wine. Next the paper will provide a list of practical solutions scientists and industry professionals can take to mitigate and adapt to the coming change in both vineyards and wineries. The third section provides suggestions for additional research on the topic, while the fourth section outlines limitations to this paper. It concludes with a highlight of major implications.

2. Review of the literature

In order to explore the impact of climate change upon global wine production and the potential challenges it could bring, this literature review will cover: (1) the definition and causes of global warming, (2) the shift in premium winegrape regions and grape variety cultivation, (3) the change in grape chemistry and the quality of wine, (4) the impact of a rising sea level and the loss of vineyard acreage, (5) the increase in insects and insect-borne diseases, and (6) the change in the quality of oak.

2.1. Definition and causes of global warming

Global warming is defined as the increase of the average temperature on the Earth. This includes both atmospheric and oceanic temperatures. Since the beginning of the twentieth century, the average global temperature has risen about 1.4° F, with about two thirds of that rise occurring since 1960 (IPPC, 2013a, 2013b). "The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change meeting every two years. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts (IPPC, 2013a, 2013b)." Though predictions vary widely, the IPCC believes that in the 21st century average global temperature could rise, if humans fail to mitigate the anthropogenic causes of global warming, by 11.5° F. With mitigation this rise could be reduced to 2° F. However, even at the lowest rise, the planet faces serious, if not catastrophic, results.

The primary cause of global warming is the "greenhouse effect." According to Venkataramanan (2011) when the Earth radiates the energy back toward space, it is sent in longer wavelengths than the energy received. While most of these longer wavelengths are still lost to space, a portion is captured by several atmospheric gases. This capture warms the atmosphere. Additionally, some of this energy is reflected back, once again, to the Earth's surface by these gases, slowly warming the surface of the Earth, especially the oceans (Tate, 2001). This process distributes heat and maintains the relative consistency of the Earth's climate, weather and ocean current patterns.

The primary "greenhouse gases" found naturally in the atmosphere are "water vapor, which causes about 36–70% of the greenhouse effect; carbon dioxide (CO_2), which cause 9–26%; methane (CH_4), which causes 4–9%; and ozone (O_3), which causes 3–7% (IPPC, 2013a)." Other greenhouse gases are soot, sulfur hexafluoride, nitrous oxide, and the chlorofluorocarbons once found in aerosol sprays (Venkataramanan, 2011). Any increase in the concentrations of these greenhouse gases would thicken the atmosphere, intensify the capture of re-radiated heat, and warm the Earth. Since the advent of the Industrial Revolution, and especially in the last half century as the global population and energy consumption have skyrocketed, this is precisely what is happening.

The increase in atmospheric greenhouse gases that causes global warming has several primary contributors: the burning of fossil fuels, widespread deforestation, the loss of natural "carbon sinks," oceanic acidification, the use of landfills, and large scale cattle and sheep ranching (Burney et al., 2013; Tate, 2001; National Geographic, 2013). The greatest contributor, however, is the rise in greenhouse gases, and the greatest contributor to the rise of greenhouse gases is the burning of fossil fuels (IPPC, 2013a). Fossil fuels are hydrocarbons formed from the buried remains of dead plants and animals that have been converted to crude oil, coal, natural gas, or heavy oils by exposure to heat and pressure in the earth's crust over hundreds of millions of years (Science Daily, 2013). According to the IPPC (2013a, 2013b, p. 2): "Fossil fuel burning has produced about three quarters of the increase in CO_2 from human activity over the past twenty years." Furthermore, coal burning, primarily for the creation of electricity, contributed 43% of total emissions; oil, for heating, contributed 34%; gasoline, primarily for transportation, 18%; and the balance is due to a variety of factors.

Deforestation is another powerful contributor to the increase of atmospheric CO_2. All plants are carbon-based and, as such, when they die, they decompose, releasing CO_2 back into the atmosphere. Large-scale removal of existing forest land, particularly by third world countries, for agriculture releases "enormous amounts of stored carbon (Venkataramanan, 2011)."

As the Earth's temperature rises, even slightly, another event occurs: the loss of "carbon sinks" (natural systems, such as arctic tundra, continental peat bogs, and oceanic phytoplankton, that store carbon over thousands of years). Tundra and peat are vulnerable to slight increases in temperature; their death and decay will release even more CO_2. However, according to Venkataramanan (2011), the greatest carbon sink are the oceans' phytoplankton reserves, holding 50 times as much carbon as the atmosphere. Rising ocean temperatures would increase the level of acid in the water ("acidification") in the form of carbonic acid causing "substantial reductions" of phytoplankton thereby releasing a potentially cataclysmic release of CO_2 as the phytoplankton reserves die. Current estimates suggest there has been a decrease in oceanic surface pH (an increase in acid) to 8.2 (a level capable of killing phytoplankton), a marker not reached in the last two million years (IPPC, 2013a).

Methane, a non-CO_2 greenhouse gas, is released from farm animals, especially livestock, and from landfills. In terms of its heat-trapping ability, a molecule of methane produces more than twenty times the warming of CO_2 (National Geographic, 2013). Soot and other non-CO_2 contaminants, primarily released from factories and other industrial emissions, contribute to the balance (Burney et al., 2013). In all, atmospheric greenhouse gases are rising precipitously and the Earth is warming. Civilization has added, in greater and greater quantities, greenhouse gases to the atmosphere.

Though some experts deny humankind's impact upon global warming, the changes in the atmosphere are undeniable. According to the IPPC (2013a, 2013b, p. 5), the "concentrations of CO_2 and methane have increased by 36% and 148% respectively" from 1750 to 2007, higher than any time in the last 600,000 years. Furthermore, readings at Mauna Loa, the world's "benchmark site" for CO_2 readings, showed atmospheric CO_2 surpassing 400 ppm for the first time in 4.5 million years, an alarming level (IPPC, 2013a). The IPCC warns that current models suggest by the year 2100 the atmospheric concentration of CO_2 could range between 541 and 970 ppm, an increase of nearly 250% since 1750. Non-CO_2 gases (dark soot, ozone, and hydrofluorocarbons), which recent research causes just under half of current global warming, are up appreciably, as well (Burney et al., 2013).

Since 1990, the yearly emissions of "carbon dioxide equivalent" have gone up by six billion metric tons annually, an increase of more than twenty percent (National Geographic, 2013). Almost 100% of the observed temperature increase over the last 50 years has been due to the increase of these gases in the atmosphere and the primary driver of this global warming is atmospheric CO_2 caused in large part by the burning of fossil fuels (Venkataramanan, 2011).

The consequence of unmitigated global warming is catastrophic: flooding sea levels, powerful weather events, changing weather patterns inducing water shortages and drought, a severe reduction of farmland, the salinization of fresh water, an insect population boom and the resultant explosion of insect-borne diseases, the extinction of species, population displacement, the interruption of economic interaction, disease, hunger, and death (Tate, 2001; Venkataramanan, 2011; IPPC, 2013a). These issues have a direct consequence to many agriculture industries, but especially to premium wine grapes around the world.

2.2. *The impact of global warming on premium winegrape regions and grape variety cultivation*

The shift in global warmth patterns may move premium grape growing regions out of areas currently devoted to that activity and simultaneously cause a shift in current grape variety cultivation. Global warming is not uniform: there is greater warming over land, with greater warming at the higher latitudes, especially in the Northern Hemisphere (IPPC, 2013a). The rising temperatures will continue to stimulate the melting of polar ice and high altitude snow pack which shall not only affect global sea level, but greatly affect oceanic currents, the great creator of global weather and climate patterns (Tate, 2001).

Models of change consistently suggest a reduction of precipitation in sub-tropical land areas and an increase in precipitation in more northerly latitudes and the equator. Additionally, changing weather patterns will bring more pressure upon fresh water supplies as some regions dry further (Hannah et al., 2013). Conversely, a melting Greenland ice sheet will stall the warm Gulf Stream, creating a colder north Atlantic and a cooling of northern European coastlines, offset by a warming of its interior. Rising temperatures worldwide will have extraordinary effect upon agriculture; however, few crops are a susceptible to minor changes in climate than grapes, especially premium wine quality grapes (Furer, 2006; Hannah et al., 2013; Tate, 2001).

The entire range of grape growing climate zones is about 10° C globally; for some grapes, such as Pinot noir, the range is an even narrower 2 °C (Santisi, 2011). The National Academy of Sciences suggests that the general shift of warmer temperatures poleward will lead to a "huge shake-up in the geographic distribution of wine production (Lallanilla, 2013)" in the next half century (Hannah et al., 2013). The practical and economic would be monumental. Premium wine producing regions would shift poleward. "Many quality wine growing regions now on the margin for secure wine production will become safe and other regions will be able to expand their grape selection (Tate, 2001)." Some areas would cease production all together (Kay, 2006; Tate, 2001). According to Tate (2001), the consequence of this warming will be the ability of Vitis vinifera to "thrive in more poleward locations than it does today," with some areas now perfect for a given cultivar ceasing to be so. To combat this warming, another study suggests a rule of thumb may be to move planting regions one Celsius isotherm further poleward for each degree of average temperature increase (Kenny and Shao, 1992). Change, however, would be global.

Region by region, climate change would shift wine production, especially in terms of grape selection. By 2100, it is possible that the United States could lose up to 81% of its premium winegrape acreage (Kay, 2006). In California, warming temperatures and a reduction in fresh water in the next half century may deliver an enormous loss of land suitable for premium grape production, especially in Napa and Santa Barbara Counties where land loss could be near 50% of current acreage (Kirkpatrick, 2011). Another study suggests that these regions would be lost completely finding only the narrow coastal bands and the Sierra Nevada left suitable for production (Kay, 2006).

Where grape production is not lost altogether, more heat-tolerant grapes of lesser quality could be planted (Kirkpatrick, 2011; Santisi, 2011). In western North American vineyard regions located in cooler climates, such as Oregon, Washington and British Columbia, the lift in temperatures could dictate that same shift to warmer grape varieties, as well (Lallanilla, 2011; White et al., 2006). This could prove to be a boon to those regions' wine production. Strangely, some forecasts include new regions' suitability, including Yellowstone and even the Yukon (Hannah et al., 2013).

In Europe, the impact of global warming on wine growing regions would be large. The loss of the Gulf Stream would chill Bordeaux and parts of Spain, forcing a replanting toward cooler climate grapes (Furer, 2006). However, other regions would become warmer. Alsace, for example, has been experiencing a shortening of the growing season and a shift of harvest from October to September in the last three decades (Furer, 2006). Burgundy may soon come to "resemble Bordeaux (Furer, 2006)." So troubling is this possibility, even the term, "climat," as an expression of Burgundian identity, is facing pressure toward redefinition (Whalen, 2010). Even the region's planting of Pinot noir may wane as the finicky grape begins to lose viability (Tate, 2001). Spain's interior may experience such change in rising temperatures and water availability, that it "may be difficult to survive" at all (Furer, 2006). Tuscany's Chianti region is finding grapes ripening far too early forcing a shift in varieties (Wine News, 2006). Vast portions of Europe on the Mediterranean coastline, especially Italy, Greece, and France, may become completely inhospitable to grape production by 2050 (Lallanilla, 2011). Southern England, by contrast, is resembling Champagne and has had several vintages of note (Furer, 2006; Wine News, 2006).

In South America, the change may be felt more in the shortening of the growing season's effect on late-ripening Cabernet Sauvignon (Hadarits et al., 2010). A change in the variance in year-to-year quality may force a focus on moving vineyards to higher elevations rather than suggest a variety shift more toward earlier ripening varieties, such as Merlot (Hadarits et al., 2010).

Other global wine regions will be impacted in different ways. Australia may dry and warm significantly. A study by the University of Adelaide concluded that by 2060 South Australia ought to experience an increase in temperatures by 2° C and a decrease in available fresh water by 30% (Ecos, 2013). According to Richard Smart, Australia's famed viticulturalist, much of Australia's Murray River may become completely untenable for grape production (Furer, 2006). This, coupled with global economic changes, may force even McLaren Vale to shift production and marketing tactics (Ecos, 2013). New Zealand is experiencing "early vital signs of imminent 'regime shifts' (Shanmuganathan et al., 2012)". Some regions may need to shift toward warmer season grapes. South Africa, too, is experiencing shifts in climatic patterns and they, like New Zealand, may need to replant vineyards with varietals that can handle increased temperatures (Confronting Climate Change, 2013). China may yet see the greatest expansion of domestic vineyards as new regions open up to vineyard capability (Lallanilla, 2011).

2.3. The change in grape chemistry and the quality of wine

The shift in climate and the resulting changes to weather patterns and carbon dioxide levels may cause shifts to grape chemistry and the resulting quality of wine. This is already being discerned worldwide. Tate (2001, p. 3) warns, "For wine production … the most miniscule modifications in proportions can produce the most major modifications in flavor." Since minor shifts in seasonal temperature "can make the difference between a poor, good, or excellent vintage … colder-than normal temperatures lead to incomplete ripening with high acid, low sugar, and unripe flavors (whereas) warmer-than-normal temperatures create overripe fruit with low acid, high sugar, high alcohol and cooked flavors (Santisi, 2011)."

An upward shift in seasonal temperature will dramatically shift the growing season thereby changing the normal pattern of grape development toward an earlier onset of flowering, veraison, and harvest (Keller, 2010). Keller (2010, p. 4) warns, "The timing of veraison may be of particular importance, because earlier veraison implies that the critical ripening period shifts towards the hotter part of the season." The consequence to grape chemistry is substantial: elevated fruit sugar, lower acid concentrations (especially malic acid), and lower anthocyanins and methoxypyrazine levels. Higher sugar delivers shifts in alcohol, altering flavors and mouthfeel. Lower malic acid, especially in whites that do not undergo malolactic fermentation, may force the addition of tartaric acid to enhance mouthfeel and microbial stability (Keller, 2010). Lower anthocyanins will reduce the "color potential" in red wines. On a positive note, however, because warmer temperatures tend to depress pyrazine accumulation and enhance their degradation, a lift in average growing-season temperatures ought to end with a lower incidence of wines with "veggie, herbaceous notes, (Keller, 2010)."

In an extensive statistical study measuring rising temperatures' effect upon Germany's winegrape production, particularly in relation to sugar levels and vineyard yields, Schultz (2010) discovered there has been a discernable difference in must sugar content over the past few decades, especially in German white varieties. Another study in Australia found temperature effects upon TA and pH levels was variety-specific: Cabernet Franc and Chardonnay experienced the greatest shifts in both TA and pH, Semillon experienced a wider variance in pH, yet Shiraz showed little change in either measurement (Sadras et al., 2013).

Additionally, it is surmised that a rise in CO_2 will change wine quality. According to Schultz (2010), a rise in CO_2 coupled to a lift in temperature and a shift in relative humidity may increase biomass, increased sugar (thus alcohol), and a decrease in acid levels all of which will affect grape aroma and flavor. Tate (2001) states, that rising CO_2 will cause faster growth and, therefore, higher sugar concentrations and thicker skin development (thus higher tannin levels). Therefore, it is a certainty that a change in climate, no matter how small, will shift grape chemistry for winegrapes currently in place.

2.4. The challenges of a rising sea level and the loss of vineyard acreage

One of the most defining evidences and consequences of global warming is a rising sea level. Over the history of the Earth, sea level has varied greatly as the earth traveled through the expanse of time as temperatures shifted on the planet. Ice caps expanded and contracted. However, in the past century, especially in the past four decades, the warming Earth has rapidly accelerated the melting of polar ice, the Greenland ice sheet, and continental glaciers (Tate, 2001; Venkataramanan, 2011; IPPC, 2013a). Though the IPCC's original projection foresaw only a lift of 0.5 m, new data have substantially changed this original assessment (Tate, 2001). The current variance swings from 0.2 m to 2.0 m, with some evidence suggesting up to 4 m (Tate, 2001; IPPC, 2013a).

According to Tate (2001), a five-meter rise in sea level would inundate some of the planet's greatest vineyards and wine producing regions with flooding. These could include portions of Bordeaux, Portugal, New Zealand, Australia's Swan district, and California's Carneros appellation. Added to the coastal flooding, more inland vineyards could face heightening levels of salinity in ground water which could affect vine growth. Earthquake is another threat, triggered by rising sea levels. Wine regions that are at risk for this are Oregon, Washington, British Columbia, Chile, Argentina, and New Zealand (Tate, 2001).

2.5. The increase in insects and insect-borne diseases

Changes in temperatures and humidity may increase the presence of insects and insect-borne diseases as their temperature limits move poleward. Many regions long believed to be climatically protected from certain pests may find themselves now open to infestation and contagion. The Glassy-winged Sharpshooter has brought Pierce's disease to California. With a lifting of temperatures, this disease may travel northward. Pierce's disease, Xylella fastidiosa, is "highly temperature-dependent…(yet with) ample moisture…a continuation of warming …will make Oregon's wine country an ideal home (Tate, 2001)." Caffarra suggests that an increase in temperature may increase a vineyard's susceptibility to the European Grapevine Moth and powdery mildew (Caffarra, et al., 2012).

New research from Penn State University suggests that other pests may be creeping northward, as well. Studying originally "the temperature-driven changes in outbreak patterns" for tea crop pest, the Tea Tortrix, a native of Japan, and its slow movement northward, the Penn State study suggests their conclusions could be applied to vineyard destroying pests, such as mealy bugs (Pseudococcus longspinus), grass grubs (Costelytra melodica) and erinose mites (Colomerus vitis), and may be "particularly valuable in management of the five European vineyard moth species, Botryosphaeria; Botryosphaeria lutea, Botryosphaeria dot idea, Botryosphaeria parva, Botryosphaeria obtuse, and Botryosphaeria stevensii, all of which are likely vectors for the various die-back diseases of grape vines (WineTech, 2013)." All of these pests may pose severe threats to more poleward resting vineyards as climate change develops (WineTech, 2013).

At the 2006 international "Global Warming and Wine Conference," Australia's Richard Smart cited a newfound presence of the pest, Hyalestes obsoletus, in northern Germany. As a vector for Bois Noir phytoplasma disease, affected vines' yields drop to zero (Furer, 2006). Smart warned, too, of another pest, the Asian Lady Beetle which has been identified in the mid-section of the United States, the US eastern seaboard, and in Ontario, as well as Italy, Belgium and the United Kingdom. Climate change and global warming will force vineyard managers to be increasingly vigilant in identifying and, then, managing a variety of warmer-weather-bound insects and diseases.

2.6. The change in the quality of oak

Changes to weather patterns and carbon dioxide levels may affect the development and quality of oak, the primary wood used to age wine in barrel (Mira de Orduña, 2010). According to Tate (2001), studies of several oak species indicate that increasing atmospheric CO_2 may accelerate the production of "tree mass" to levels twice the rate as levels previously observed. Tuscan oak forests of Quercus ilex, American forests of Quercus alba, and European forests of Quercus robur have been observed to exhibit increasing growth rates. The result of this quickened growth may be that the "size and number of conducting vessels in the stems increase… (creating) expanded passages that are more vulnerable to damage and failure" as barrels (Tate, 2001, p. 8). Another study of the oak, Quercus rubra, suggests that, when subject to increased CO_2, a measurable decrease in the concentration of the tannin, ellagitannin, results; this reduction may affect the overall quality wine barrel by lessening the tannins released into the finished wine.

3. Practical solutions vineyard management and wineries may take to mitigate and adapt to the coming change

This review of the literature has demonstrated that global warming has direct and, sometimes, quite severe implications for both vineyard management and wineries. The questions remaining are not if, or how, global warming is occurring but, rather, how the global wine industry, should adjust to the change (Battaglini et al., 2009; Lereboullet et al., 2013). Therefore, a series of practical solutions are provided for both vineyards and wineries below.

3.1. For vineyards, existing and newly planted

1) To offset rising temperatures, consider improving the soil–water balance through a change in canopy management to provide additional shade so as to reduce sugars and increase acids. Be aware, however, that increased shading may still cause higher pyrazine levels and a possible reduction in berry coloration (E-VitiClimate, 2012; Keller, 2010). It is important to note, as well, that several studies have suggested traditional vineyard management techniques, including canopy management, pruning and weeding, have been insufficient in the last decade to combat higher temperatures and drier conditions (Lereboullet et al., 2013).
2) To offset rising temperatures, consider nighttime harvesting and quicker delivery of the berries to the winery to assure cooler berry temperatures to avoid spoilage (E-VitiClimate, 2012).
3) To minimize soil erosion and to maximize nutrient and water storage due to changes in precipitation patterns, consider the introduction of winter cover crops in areas capable of supporting such crops in the winter (Schultz, 2000).
4) To offset reduced water supply and to mitigate against global warming, consider the "reuse, treatment and

recycling of water to minimize waste," as well as reducing the costs of water usage and removal (E-VitiClimate, 2012). The wine producers of Australia's McLaren Vale are considering the implementation of a "recycled water scheme" to combat a "drying climate (Ecos, 2013)".

5) To offset reduced water supply (as well as improving nutrient delivery), consider improving the soil–water balance through (a) more effective irrigation delivery via drip irrigation (to control and minimize delivery loss), (b) enhanced soil structure/composition (for both water retention and nutrient load), (c) more effective erosion control and nutrient storage through the use of cover crops, and (d) a reduction of evapotranspiration by employing less frequent tilling and cultivation (E-VitiClimate, 2012; Keller, 2010; Lereboullet et al., 2013). Carefully examine future water needs and supply against current environmental research and literature (Hadarits et al., 2010). Effective drip-irrigation may become increasingly more necessary to continue constant yields and consistent wine styles (Lereboullet et al., 2013).
6) To offset reduced water supply to increase water use efficiency (WUE) and to promote optimal grape maturity and wine quality, consider deficit irrigation strategies, such as partial root drying (RDI), sustained deficit irrigation (SDI), and regulated deficit irrigation (RDI) techniques (Fraga et al., 2012).
7) To offset an increase in heat, drought and light intensity in the vineyard that may dramatically affect phenolic metabolism (as well as grape development and chemical composition), consider heat and light abating cultural practices, such as canopy management and irrigation techniques, to adjust and maintain berry and wine quality (Teixeira et al., 2013).
8) To offset an increase in vineyard heat, consider an improvement to cooling techniques, such strategic vine orientation/trellising practices and water-efficient micro-misters (Hannah et al., 2013).
9) To delay the earlier onset of fruit maturation and extend it to the relatively cooler end of the growing season, consider markedly increasing the vine crop load (Keller, 2010).
10) To offset the effect of an early harvest date, consider the more measured use of nitrogenous nutrients in the vineyard (Keller, 2010).
11) To offset a substantial change to vineyard climate, consider the grafting over or complete vineyard reinstallation to grapes more closely adaptable to the new climatic and weather conditions in order to produce grapes for premium wines. If new installation, assure proper choice of rootstock to combat new climate conditions, as well as new pest and disease conditions (Phylloxera, nematodes, mildew, bacteria and viruses) (E-VitiClimate, 2012; Kirkpatrick, 2011).
12) To offset increased sunlight, consider using different training techniques and row orientation. In many high-heat and sunlight regions, the north-south orientation causes difficult western exposure in the afternoon (Keller, 2010).
13) To offset the increase in pests, consider implementing an Integrated Pest Management (IPM) system, an "ecosystem-based management practice that integrates biological, cultural, physical, and chemical tools to manage pests and diseases in the vineyard (E-VitiClimate, 2012)." This helps mitigate, too, against climate change by reducing the reliance upon agrochemicals and the subsequent chemical emissions via their decomposition, as well as the emission caused by their initial production (E-VitiClimate, 2012). Butt and Copping (2000) suggest the use of biological control agents so as to reduce other collateral environmental impacts.
14) For conditions that are too great for adaptation in the existing vineyard, consider moving to more poleward or higher elevation sites following extensive meso- and micro-climatic site evaluations (E-VitiClimate, 2012). Fraga et al. suggests considering a range of adaptations, including land allocation and varietal shifts (Fraga et al., 2012).
15) To mitigate against global warming, consider lessening your "carbon-footprint" by reducing overall carbon use (Jones and Webb, 2010).

3.2. *For wine production (in addition to suggestions listed above)*

1) To offset warmer temperatures in the winery, consider the use of cooling equipment to assure completed primary and malolactic fermentations. Though factors that may limit fermentation are low pH values, nutrient deficiencies, high ethanol levels, and high concentrations of SO_2, Mira de Orduña suggests an increase in winery cooling capacity (Mira de Orduña, 2010). Be aware that early harvesting and higher ambient temperatures may greatly affect aroma/flavor compounds and "exacerbate oxidative reactions in pre-fermentation stages, such as destemming, crushing, pressing, and settling (Mira de Orduña, 2010)."
2) To offset warmer temperatures in the winery, consider a reinspection of cellar hygiene practices and the use of antimicrobials and antioxidants (E-VitiClimate, 2012).
3) To offset the effect of higher sugar and alcohol levels during fermentation, consider more alcohol-tolerant yeast strains (Vink et al., 2009).
4) To offset higher sugar levels in the must, consider the employment of sugar reducing techniques such as ultrafiltration and reverse osmosis (E-VitiClimate, 2012). Mira de Orduña warns that "musts with high sugar concentrations cause a stress response in yeast, which leads to increased formation of fermentation co-products, such as acetic acid. If not controlled by acid addition, the higher pH can lead to significant changes in the microbial ecology of musts and wines and increase the risk of spoilage and organoleptic degradation (Mira de Orduña, 2010)."
5) To offset a reduction of acidity so as to promote microbiological/microbial stability and reduce the

likelihood of stuck fermentations, consider acidification (E-VitiClimate, 2012; Mira de Orduña, 2010).

6) To offset vintage variability, particularly in regard to wine complexity and style, carefully consider new blending techniques, including the blending of wines from different terroirs and regions (Vink et al., 2009).
7) To offset early harvest and lower acid level in white wines, consider leaving white wine on their lees longer so as to conserve fruit-aroma compounds, protect them from oxidation, and increase the release of mannoproteins (E-VitiClimate, 2012).
8) To offset the early onset of ripening fruit, remember to schedule harvest activities earlier to avoid the rush to secure labor and equipment in a more compacted time-frame (E-VitiClimate, 2012).
9) To mitigate the effect of the burning of fossil fuels in the production of electricity consider solar renewables in the form of solar thermal and photovoltaics. The potential savings for a commercial winemaking establishment's integration of a 'small' solar installation is an 18% savings in energy used when compared with the global winemaking industry as a whole (Smyth and Russell, 2009).
10) To maintain operational viability and competitiveness, develop and implement a system of "planned change so as to anticipate future climatically-induced impact and, thus, decrease vulnerability (Lereboullet et al., 2012)".
11) To mitigate the effect of the burning of fossil fuels in the production of electricity, consider, in addition to the clean, renewable sources of energy, the employment of an energy consumption-monitoring plan to optimize the use of energy (E-VitiClimate, 2012).

4. Additional research needed

Despite the strides in research that have been achieved regarding the impact of global warming on the wine industry, additional research is needed. Dr. Hans Schultz of the Geisenheim Research Centre in Geisenheim, Germany, suggests three areas to consider: "one related to the lack of knowledge about how plants, micro-organisms and pathogens will respond to a rise in CO_2 concentration, temperature and a possible lack of water simultaneously under field conditions; the second related to evaluation of the carbon budget of vineyards and the release of nitrous oxide and possibly methane, two of the most potent greenhouse gases, from viticultural production systems and the development of mitigation strategies; and the third on the broader aspect of resource management in the production chain within the wine industry and possibilities for its improvement (Schultz, 2010, pp. 113–114)."

Dr. Nicholas and her team (Nicholas et al., 2011) studying, specifically, the effect of climate change upon the Pinot noir of Carneros and southern Sonoma County, suggests, "Future work should pursue questions at both the vineyard and the regional scale. At the vineyard scale, environmental measurements at individual vines for variables such as canopy or cluster temperature and light, and plant and soil water status, would help to explain the tremendous variability observed within vineyards and elucidate the role of climate and particularly temperature on fruit composition (p. 1564)."

Further, improved observations and models of grapevine development and the drivers of grapevine phenology are important for accurate projections of climate change impacts. On the regional and larger scale, a robust examination of climate effects on viticulture would require a large-N study over many sites and years to detect trends (Nicholas et al., 2011).

Additionally, basic research on the business impact of environmental changes should be tracked on a more regular basis. This could include a cost-benefit analysis at the individual vineyard and winery level, as well as regional and country level. This information could then be compared on an international basis. It would be useful to track this on a longitudinal basis to determine if the costs associated with implementing new solutions result not only in creating a more sustainable business but a positive return on investment in the short and/or long term. Though this is being done to some extent, by such program such as the California Sustainable Winegrowing Program, it could be expanded upon.

5. Limitations

There are several limitations to this paper. A major issue is that local conditions in different wine regions of the world will influence adaptation strategies. For example, while some wine regions may become warmer, others will become cooler. Likewise weather patterns will be more random, causing decimation of a vineyard by hail one year, whereas extreme heat or rain may occur the next. Therefore suggested solutions may not be applicable in all cases.

A second limitation is that, though the practical suggestions provided here are intended to be useful, the element of uncertainty associated with climate change must be recognized. Variables here are defined in a deterministic manner, but history shows that socio-economic issues, politics, and regulations often impact vineyard and production practices just as much as environmental changes. Therefore a strategic long-term perspective should be assumed, and the limitations expressed here taken into consideration.

6. Implications and conclusion

This paper provides a review of the literature on the subject of global warming and its impact on vineyards and winemaking. The evidence suggests that global warming will affect winegrape and wine production, not only in grapevine physiology and biochemistry, but in the production methods used to make wine (Schultz, 2010). This implies that viticulture managers and producers need to consider a wide variety adaptation and mitigation methods to preserve their wines' quality, identity, and profitability (Bernetti, et al., 2012).

A series of practical solutions for both vineyards and wine production is provided. Implications for vineyard managers and winemakers are to determine how global warming will impact their particular location, and then analyze the list of practical solutions to see which actions will be beneficial to their site and product.

It is recognized that many progressive viticulture regions around the world have already taken steps to mitigate some of these issues. Certifications for sustainable and environmentally friendly practices are being adopted more frequently by producers around the world. Some of these certification and organizations include: ISO 14001 Environmental Management, FIVS Global Wine Sector Environmental Sustainability Principles, New Zealand Winegrowers' Sustainable Winegrowing, Demeter's Biodynamic Certification, California Sustainable WineGrowing Certification, Fish Friendly Farming, Napa Green and many other environmental and organic certifications around the world for wine. These types of positive efforts should continue, multiply, share best practices and coordinate data tracking.

In conclusion, wine's future is tied inextricably to a vital Earth and a vital population. Grape growers and winemakers must understand both the dire condition of the planet and the small, but significant, role their industry holds in the human matrix. They must seek, therefore, in a responsible manner, their proper and effective role in the adaptation to and the mitigation of global climate change. The future of the wine industry is dependent upon an effective course of action. The Romans declared, "Vino veritas," or "in wine there is truth (Jones and Webb, 2010)." The simple, yet tragic, truth is the Earth's climate is changing. How the wine industry responds will determine if the industry is to survive.

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