THE STATE OF THE CLIMATE

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Abstract:

Context and purpose of the study

The climate has warmed over the past century or more bringing about changes in numerous aspects in both earth and human systems. One of these systems, agriculture, is strongly influenced by climate, which largely determines what type, where, and how crops can be grown. Within agriculture, growing grapes and wine production are a sensitive long-lived specialty crop system where the environmental and economic sustainability of quality production is at risk from a changing climate. As such, this work examines the current state of the climate globally and within wine regions to provide a framework for these changes historically and into the future.

Material and methods

Summaries of global observations and climate model projections are utilized to provide a current state of the climate. Spatial climate data for 22 prominent wine regions worldwide are also used to assess characteristics and trends in annual and growing season temperature and precipitation.

Results

Growing season temperatures across the 22 regions for 1901-2017 averaged 16.6°C, ranging from 13-15°C in the cooler regions to 19-21°C in the warmest regions. Over all 22 regions, the average decadal temperature trend during the growing season is 0.12°C while the average change over the entire time-period is 1.4°C. While some regions show higher interannual variability and more gradual warming trends, many regions show stronger trends and more rapid warming. Annual temperature changes closely mirror those during the growing season (not shown).

For precipitation, the results detail a wide range in year-to-year variability in precipitation, with some regions experiencing consistent annual and growing season precipitation amounts while others are much more prone to extreme dry periods. The average percentage of growing season to annual precipitation across these regions is 45%, with those regions lower than average being predominately west coast regions and those with higher percentages being largely in continental climates with greater summertime thunderstorm activity or where greater oceanic influences exist. Precipitation trends for the 22 wine regions are few, following observations globally and in many other wine regions during the last 50 years.

Keywords: viticulture, wine, terroir, climate, climate change.

1. Introduction

While it is clear from historical evidence that changing climates are a part of the Earth's natural adjustments to both internal and external forces (e.g., volcanic eruptions and solar variability), more and more evidence is pointing to increasing human impacts on our climate (IPCC, 2014). From changing atmospheric concentrations of greenhouse gases, to altering the surface through deforestation, desertification, and urbanization, our role in changing the Earth's energy balance and, therefore, climate has become more apparent (IPCC, 2014; USGCRP, 2017). Evidence of warming in the climate system is unequivocal (IPCC, 2014) with warming in the Earth's surface, in the atmosphere, and across the world's oceans, including declining amounts in snow and losses in ice mass, along with rising sea levels. While a changing climate is a pervasive factor across all natural Earth and human-based systems, it's role in agriculture poses issues related to sustaining and enhancing crop productivity (USGCRP, 2018) across both broadacre crops (e.g., corn, wheat, soybeans, rice) and specialty crops (e.g., coffee, cacao, avocados, winegrapes).

Regional weather and climate conditions play a significant role in the productivity of vineyards and the quality of its grapes and resulting wine (Jones et al. 2012). As such, growing grapes for wine production is vulnerable to numerous atmospheric factors that operate over a wide range of timescales, from short-duration weather events (e.g., frost or hail) to medium-range events (e.g., heat stress, droughts) to longer term trends in temperatures or precipitation (from decades to centuries). Weather and climate therefore drive variations in wine production and quality, which together drive regional economics across the whole winemaking sector (Jones and Davis, 2000; Santos et al., 2011; Urhausen et al., 2011).

Grapevines are influenced by air temperature throughout their vegetative cycle (Jones, 2006; Keller, 2010). Excessively low temperatures during the winter can kill or severely limit viability (Keller, 2010) and during the growing season may limit grapevine development and berry ripening (Cyr et al., 2010). Although grapevines require sufficient heat accumulation for their growth and physiological development, temperatures above what is considered optimum for a given cultivar may lead to unbalanced ripening and potential shifts in harvest timing (Duchêne and Schneider, 2005). Furthermore, prolonged periods with temperatures greater than 30-35°C may affect secondary metabolism and alter sugar accumulation and acid concentration in berries (Mori et al., 2007).

While viticulture and wine production are largely done across regions with relatively dry climates, the overall precipitation amount is critical factor in controlling soil water balance and plant water status, particularly in non-irrigated vineyards. During the spring flowering period, excessive precipitation can influence flowering and fruit set, while during the summer too much moisture can adversely affect berry quality and can lead to increases in disease pressure in vineyards (Cyr et al., 2010). Severe dryness can also be problematic, especially during bud break to flowering, and if prolonged over the growing season may reduce grapevine growth, limit sugar development and lower yields (Fraga et al., 2013; Koufos et al., 2017).

Given the importance of climate and its role in viticulture and wine production, this research describes the current state of the climate as summarized from numerous national to international agencies in their most recent reports and examines conditions and trends in many of the world's prominent wine growing regions.

2. Material and methods

The main overview is provided from the Intergovernmental Panel on Climate Change and the United States Global Change Research Program. The work is supplemented with a climate analysis using data from the CRU TS 3.23 global temperature and precipitation database (Harris et al., 2014). The data is gridded at 0.5° x 0.5° representing a spatial average of approximately 50 km at the latitudes of 22 wine regions in Europe, South Africa, Australia, New Zealand, Chile, Argentina, Canada, and the United States (Table 1).

Monthly temperature and precipitation data were extracted from the CRU TS 3.23 global database for the grid cells encompassing each of the wine regions for 1901-2017 (Table 1). The monthly data were aggregated to the annual and growing season periods. The growing season period used was April-October in the Northern Hemisphere and October-April in the Southern Hemisphere. While other growing season periods could have been used (March-September, September-March) a sample analysis showed that there were no significant differences in the trends and only minor differences in the sums or averages. Simple linear regression analysis was used with trends evaluated using the Mann–Kendall test (Yue et al., 2002), being considered significant if $p < 0.05$.

3. Results and discussion

3.1. *IPCC and USGCRP Summaries*

Annual surface air temperatures averaged globally have increased approximately 1.0°C since 1901 (USGCRP, 2017). With the five warmest years on record happening during the past five years (2014-2018) and the 20 warmest years occurring over the past 22 years, we are likely seeing the warmest period in the history of modern civilization (IPCC, 2014). Recent decades have also seen more climate-related weather extremes, which have been particularly impactful on human safety, infrastructure, agriculture, water quality and quantity, and natural ecosystems. The result has been increasing direct and insured losses from weather and climate related disasters both globally (IPCC, 2014) and regionally (USGCRP, 2018). For example, heavy rainfall is increasing in intensity and frequency across many regions globally and heatwaves have become more frequent while extreme cold temperatures and cold waves are less frequent but still occur. Additional impacts have been seen in the incidence of large fires in the western United States and Alaska, Australia, and Portugal for example. These events have resulted in the loss of life and property, brought profound changes to regional ecosystems, and affected grape growing and wine production in some regions (USGCRP, 2018). In addition, many mountainous regions worldwide have experienced annual trends toward earlier spring melt and reduced snowpack, which affect water resources for both society and agriculture. While the IPCC (2014) indicates that there is lower confidence in observed global-scale trends in droughts, due to lack of direct observations, regional observations in some areas (e.g., California and Australia) do show change in drought frequency and severity (USGCRP, 2018).

3.2. *Observed Changes in Wine Regions*

Growing season temperatures across the 22 regions (i.e., April through October in the Northern Hemisphere and October through April in the Southern Hemisphere) for 1901-2017 averaged 16.6°C, ranging from 13-15°C in the cooler regions (Surrey, Tasmania, Willamette Valley, Burgundy) to 19-21°C in the warmest regions (La Mancha, Stellenbosch, Mendoza, Perth, and Madera). Figure 1 shows time series for four locations across cool to hot wine producing regions for 1901 to 2017. Each region exhibits statistically significant warming averaging 0.14°C per decade and a period of record warming ranging from 1.2°C in the Surrey, England region to 1.8°C in the Perth, Australia region. Table 1 gives summary statistics for 22 wine regions from the same database. Over all 22 regions, the average decadal trend is 0.12°C while the average change over the entire time-period is 1.4°C. While some regions show higher interannual variability and more gradual warming trends (Walla Walla, Nauosa; R^2<0.15, 0.07-0.09°C per decade), many regions show stronger trends and more rapid warming (Douro, Sonoma, Napa, La Mancha, Rioja; R^2>0.50, and 0.14-16°C per decade). Annual temperature changes closely mirror those during the growing season (not shown).
While average annual precipitation has increased since 1901 over the mid-latitude land areas of the Northern Hemisphere, the changes are less consistent than temperature trends due to high spatial and temporal variability (IPCC, 2014). Similarly, observed changes in precipitation in wine regions around the world have been fewer than those seen with temperature (Jones et al., 2012). For example, over the last 50 years across western US wine regions there were no trends in annual, winter, or growing season precipitation (Jones and Goodrich, 2008), however bloom period rainfall showed small positive trends in 7 of the 10 regions and ripening period rainfall exhibited small declining trends in 6 of the 10 regions. Annual precipitation averaged across Australia has slightly increased since 1900, however a declining trend in winter rainfall persists in southwest Australian wine regions and autumn and early winter rainfall has mostly been below average in southeast wine regions since 1990 (CSIRO & BOM, 2015). In Europe, annual precipitation since 1960 shows an increasing trend in northeastern and northwestern Europe, and a decrease in some parts of southern Europe (European Environment Agency, 2017). Mean summer precipitation has significantly decreased in most of southern Europe, while significant increases of up to 18 mm per decade have been recorded in parts of northern Europe. Examining nine wine regions across Europe, Jones et al. (2005b) found slight increases in annual precipitation in two regions but no trends in seasonal precipitation. For Spain, Moreno et al. (2005) show trends to much drier springs and summers and lower annual rainfall, while Ramos et al. (2008) also found declining precipitation during the spring and summer, that when combined with the observed warming in the same regions resulted in an increased water demand of 6-14% in already semi-arid regions.

Annual and growing season precipitation were assessed using the same CRU TS 3.23 global database used for temperatures (Figure 1 and Table 1). Annual precipitation for the 22 regions averages 741 mm, ranging from just under 200 mm in the Mendoza, Argentina region to just over 1200 mm in the Willamette Valley of Oregon (Figure 2). The highest annual precipitation experienced during 1901-2017 and over all regions, was during the 1983 El Niño in the Sonoma, California region (1879 mm), while the lowest annual precipitation was in 2010 in the Mendoza, Argentina region (55 mm) (not shown). The lowest coefficient of variation (CV), indicative regions with the lowest year to year variability in precipitation, is found in the Marlborough, Bordeaux, and Niagara regions (CV = 11-14), while the highest is found in the Curico, Madera, Mendoza, Napa, and Sonoma regions (CV = 30-33). Growing season precipitation averages 324 mm across the 22 regions with the Madera, California region typically having the driest growing seasons (~50 mm) and the Marlborough, New Zealand region the wettest (~500 mm). During the 1901-2017 period, the highest precipitation experienced during the growing season was nearly 850 mm in 1951 in Marlborough while the driest growing season experienced was in the Curico, Chile region in 2009 at less than 5 mm (Figure 2). The growing season precipitation coefficient of variation closely follows the CV values for annual precipitation, with the only exception being the Mendoza region, which is closer to the overall average CV during the growing season. This is also reflected in the percentage of growing season to annual precipitation experienced in these locations with the Mendoza region at 84% due to the prevalence of summer thunderstorm activity (Figure 2). The average percentage of growing season to annual precipitation across these regions is 45%, with those regions lower than average being predominately west coast regions in Chile (the lowest at 14%), California, Australia, and the Douro Valley of Portugal, along with South Africa.

Precipitation trends for the 22 wine regions are fewer than with temperature trends, following observations globally (IPCC, 2014) and in many other wine regions during the last 50 years (Jones et al., 2012). Four regions (Burgundy, Mendoza, Niagara, Walla Walla) exhibit trends toward higher annual precipitation, while three regions (Curico, Perth, and Stellenbosch) show declining trends (Table 2). During the growing season, only four regions exhibit trends (Burgundy, Douro, Mendoza, and Niagara) with each showing increasing trends ranging from 54-115 mm. Seasonal precipitation trends have also been few. While Burgundy and Marlborough have seen slight increases in wintertime precipitation, Curico and Perth have both seen trends toward drier winters (Table 2). Spring precipitation has trended higher in the regions in the Pacific Northwest of the United States (+40-50 mm during MAM), while Stellenbosch has trended lower (-52 mm during SON). Only two locations exhibit summer precipitation trends, with both the Mendoza and Niagara regions increasing by ~30-45 mm. For the fall period, only two locations show trends with the Curico region experiencing drier falls (-74 mm) and the Niagara region seeing wetter falls (+72 mm) (Table 2).

3.2. *Predicted Changes Globally and in Wine Regions*

Globally, the mean surface temperature is projected to increase at approximately 0.2°C per decade, and is likely to reach values between 1°C and 6°C higher than current temperatures at the end of the 21st century (IPCC, 2104). Temperature changes of this magnitude will likely result in remarkably different impacts on the Earth's ecosystem, as environmental and socioeconomic systems present a range of nonlinear responses to given changes in temperature. Furthermore, regional trends and impacts will vary resulting in stronger or weaker responses than the global average, which highlights the need for more fine-scaled regional climate modeling assessments (Christensen et al. 2007). While there is substantial confidence in our current climate modeling efforts, it is important to note that future projections contain uncertainties based upon model limitations, levels of greenhouse gas emissions, and those associated with fully understanding the complexities of carbon cycling within Earth's ecosystems (Denman et al. 2007; Meehl et al. 2007; Fraga et al. 2013).

Predicted changes in future climates related to growing grapes and wine production have been documented by many studies. Examining spatial changes in suitable temperature regimes, Jones (2007) found that the broad temperature bounds for viticulture of 12-22°C during the growing season shift 150-300 km poleward in both hemispheres depending on the emission scenario. The predicted shifts are shown to be marginally greater on the poleward fringe compared to those on the equatorial fringe in both hemispheres. However, the relative area of land mass that falls within the 12-22°C isotherms across the continents expands slightly in the Northern Hemisphere while contracting in the Southern Hemisphere due to land mass differences.

Examining changes in many of the world's prominent wine regions, Jones et al. (2005a) found an average warming of 2°C is predicted in the next 50 years. For regions producing high quality grapes at the margins of their climatic limits, the results suggest that future climate change might exceed climatic thresholds such that the ripening of balanced fruit required for existing cultivars and wine styles will likely become progressively more difficult. In other regions, historical and predicted climate changes could push some regions into more optimal climatic regimes for the production of current cultivars. In addition, the warmer conditions has lead to even more poleward locations potentially becoming more conducive to grape growing and wine production. Jones and Schultz (2016) found that extreme poleward viticulture is now found at roughly 57°N in Sweden and Denmark in the Northern Hemisphere and above 45°S in Argentina and New Zealand. The research also found average trends of 0.17°C warming/decade and an absolute increase in temperature of 1.4°C during the late 1800s through 2015 averaged across 16 locations on four continents.

For the contiguous United States, annual average temperature over the next few decades (2021–2050) are expected to rise by about 1.4°C, relative to the recent past (USGCRP, 2017). Lobell et al. (2006) examined the impacts of climate change on yields of perennial crops almonds, walnuts, avocados, winegrapes, and table grapes in California. The results show a range of warming across climate models of ~1.0-3.0°C for 2050 and 2.0-6.0°C for 2100 and a range of changes in precipitation from -40 to +40 percent for both 2050 and 2100. Winegrapes showed small yield declines and substantial spatial shifts in suitability to more coastal and northern counties. White et al. (2006) estimated that potential premium winegrape production area in the conterminous United States could decline by up to 81 percent by the late 21st century. The research found that increases in heat accumulation will likely shift wine production to warmer climate cultivars. Additionally, the modeling efforts indicated that while frost constraints will be reduced, increases in the frequency of extreme hot days (>35°C) in the growing season have the potential to severely challenge or completely eliminate winegrape production in many areas of the United States. Furthermore, grape and wine production will likely be restricted to a narrow west coast region and the Northwest and Northeast, areas where excess moisture is already problematic (White et al. 2009). Jones (2007) found that for a 1.0°C warming (roughly a 15 percent increase in growing degree days) by 2049, the area of the western U.S. in Winkler regions I-V increases 5 percent from 51 to 56 percent and at +3.0°C warming (roughly a 30 percent increase in growing degree days), increases by 9 to 60 percent. Overall the changes show a reduction in the areas that are too cold from 42 to 24 percent while the areas that are too hot increase from 7 to 16 percent in the greater warming scenario (Jones, 2007). Similarly, by individual Winkler regions there are shifts to predominately more land in region I with smaller changes to region II-V. Spatially the shifting of regions occurs toward the coast, especially in California, and upwards in elevation (most notably in the Sierra Nevada Mountains). Other regions show large scale shifting from one Winkler region to another (e.g., Willamette Valley shifting from predominately region I to region II).

Examining changes in the suitability for viticulture in Europe, Stock (2005) shows increases of 100-600 heat units (Huglin Index) that will likely result in broad latitudinal shifts with new areas on the northern fringes becoming viable, changes in cultivar suitability in existing regions, and southern regions that may become so hot that overall suitability is challenged. Moriondo et al. (2013) modeled the impact of climate change on the distribution of grapevine cultivated areas in many important European wine regions using bioclimatic indices and water deficit as predictor variables. The research calibrated current conditions using the Random Forest model, then applied future climate conditions as simulated by HadCM3 General Circulation Model (GCM) to predict the possible spatial expansion and/or shift in potential grapevine cultivated area. Projected changes in climate resulted in a progressive warming in all bioclimatic indices along with increasing water deficit over much of Europe and specifically over the wine regions studied. Responses to the warmer and drier conditions included progressive shifts of existing grapevine cultivated areas to the north–northwest of their original ranges and expansion or contraction of the wine regions due to changes in within region suitability for grapevine cultivation. Wine regions with warmer climatic conditions from areas around the Mediterranean basin today (e.g., the Languedoc, Provence, Côtes Rhône Méridionales, etc.) were shown to potentially shift the most over time. Overall Moriondo et al. (2013) showed the potential for dramatic changes in the landscape for winegrape production in Europe due to changes in climate. Furthermore, to examine grapevine responses to climate change, Lebon (2002) used climate model output to show that the start of Syrah ripening (véraison) in Southern France would shift from the second week of August today to the third week of July with a 2°C warming and to the first week of July with a 4°C warming. Additionally, the research found that significant warming during maturation and especially at night would disrupt flavor and color development and ultimately the wine's typicity.

For Australian wine regions, Webb et al. (2008) analyzed climate change scenarios showing that temperatures by 2070 are projected to warm by 1.0-6.0°C increasing the number of hot days and decreasing frost risk, while precipitation changes are more variable but result in greater growing season stress on irrigation. The temperature changes projected for Australia have been linked with the potential to reduce wine quality (Webb et al. 2008), with southerly and coastal shifts in production regions being the most likely alternative to maintaining viability. Also for Australia, Hall and Jones (2008) modelled growing season climates finding that 21 of the 61 recognized wine regions in the country would be warmer than the estimated growing season temperature thresholds for suitability by 2070 without further adaptive measures.

In South Africa, regional projections of rising temperatures and decreased precipitation are likely to put additional pressure on both the phenological development of the vines and on the necessary water resources for irrigation and production (Carter, 2006). The research implies that the practice of winemaking in South Africa is likely to become riskier and more expensive with the most likely effects being shifts in management practices to accommodate an increasingly limited water supply. The author notes that the situation will likely exacerbate other economic issues such as increases in the price of wine, a reduction in the number of wine growers, and need for implementation of expensive and yet unknown adaptive strategies (Carter, 2006). Together these studies, and those detailed previously, indicate that the challenges facing the wine industry include more rapid phenological development, changes in suitable locations for some cultivars, a reduction in the optimum harvest window for high quality wines, and greater management of already scarce water resources. The extreme drought conditions in South Africa during 2015-2017 appear to be a sign that the risk of drought conditions such as experienced during this period has increased by a factor of three during the recent past and is likely to increase another threefold with 1-2 degrees of warming in the coming decades (Otto et al. 2018).

4. Conclusions

The global atmospheric carbon dioxide (CO2) concentration has now passed 400 parts per million (ppm), a level that last occurred about 3 million years ago, when both global average temperature and sea level were significantly higher than today (USGCRP, 2017). Continued growth in CO2 emissions over this century and beyond would lead to an atmospheric concentration not experienced in tens to hundreds of millions of years, and there is substantial evidence that the magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases (especially carbon dioxide) emitted globally (IPCC, 2014). Without major reductions in emissions, the increase in annual average global temperature relative to preindustrial times could reach 6°C or more by the end of this century. The last few years have also seen record-breaking, climate-related weather extremes, and the last five years have been the warmest years on record for the globe (USGCRP, 2017). Furthermore, there is broad consensus that the further and the faster the Earth system is pushed towards ever greater warming, the greater the risk of unanticipated changes and impacts, some of which are potentially large and irreversible (IPCC, 2014).

The IPCC 5th Assessment Report (5AR) provides evidence on the general agreement among observations from different measurement techniques, all documenting a clear upward trend in the global mean surface temperature in recent decades (IPCC, 2014). While there are clearly significant changes in the average temperatures both annually and across most seasons, climate variability has also increased along with the frequencies of occurrence and strength of some extremes, including precipitation (droughts and heavy rain events) and temperature (heat waves, hot days/nights) extremes (Trenberth et al. 2007; Andrade et al. 2012). Furthermore, the trends observed in the recent past can only be reproduced by climate modeling when anthropogenic forcing is taken into account (Hegerl et al. 2007).

For agriculture in general, historic observations and future modeling efforts related to climate change reveal that the changes have had and will likely continue have further impacts and challenges to the overall sustainability of current production systems. For viticulture and wine production, the climate structure of the various winegrowing regions worldwide are critical determinants of the suitability of these regions to given cultivars, their potential wine style, and the region's overall productivity. It appears that the observed warming over the last 50 years has been largely beneficial for viticulture in many regions through longer and warmer growing seasons with less risk of frost (Jones et al. 2005a). However, the trends appear to be more influential on the poleward fringes by providing more consistent ripening climates for existing cultivars, making warmer climate cultivars more viable or opening up once forgotten regions again (e.g., southern England; Jones and Schultz, 2016). On the other hand, already hot regions have experienced warmer and generally drier conditions that have produced various challenges in ripening balanced fruit.

The changes also strongly suggest that shifts in climate will likely be evidenced mostly through more rapid plant growth and out of balance ripening profiles. Evidence of these changes have been recorded in some regions where warming conditions have led to earlier phenology that has been related to higher sugar levels, lower acid levels, and higher alcohol levels. For example, alcohol levels rose 2.5 percent in Riesling in Alsace during 1972-2002 (Duchêne and Schneider, 2005) as sugar levels rose and acidity levels declined. Similar influences on fruit and wine composition have been found in Australia with increases in alcohol content of both red and white wines (1.7 and 1.0 percent, respectively) during 1984-2004 (Godden and Gishen, 2005) and Napa where average alcohol levels rose 12.5 to 14.8 percent from 1971-2001 while acid levels fell and the pH climbed (Vierra, 2004). Finally, harvests that occur earlier in the summer, in a warmer part of the growing season (e.g., August or September instead of October in the Northern Hemisphere) will result in hotter harvested fruit and potentially desiccated fruit without greater irrigation inputs (Webb et al., 2008).

While our understanding of the role climate structure and suitability plays in viticulture and wine production is generally well developed, the role that climate variability and climate change have on wine quality and productivity are now being studied more due to the economic impacts that they have and/or potentially could have on the industry. One important aspect to note is that climate change impacts on viticulture and wine production have been and are likely to continue to be highly variable, both geographically and across cultivars. Therefore, more applied research at the regional level is needed to better understand the range of variability that a region, or even an individual cultivar, can reliably produce quality wine in as growers continually attempt to minimize vintage variations in grape yield and quality (Keller 2010b).

Finally, increases in technology, better plant material, and better vineyard management have come at the same time as the warming trends and these adaptations have allowed growers to meet some of these challenges. However, the projections for future climate change will likely be more rapid and to a greater magnitude than our ability to adapt without increased understanding of the impacts and advances in plant breeding and genetics (Bisson et al. 2002). Furthermore, while most of the climate change discussion in this paper and within many other studies tends to focus on temperature-related impacts, other potential issues affecting grape and wine production and quality include changes in vine growth and fruit quality due to a higher CO_2 concentration in the atmosphere, potential increases moisture stresses in water-limited regions, and changes in the presence or intensity of pests and vine diseases. Even with our current state of climate science, much uncertainty still exists in the exact spatial and temporal nature of changes in climate at the regional level. Therefore, the wine industry will need to be proactive in monitoring the local to regional climate and assessing the various impacts on the plant system and fruit productivity and quality, and be ready to implement appropriate adaptation strategies, be willing to alter cultivars and management practices or controls, or mitigate wine quality differences by developing new technologies.

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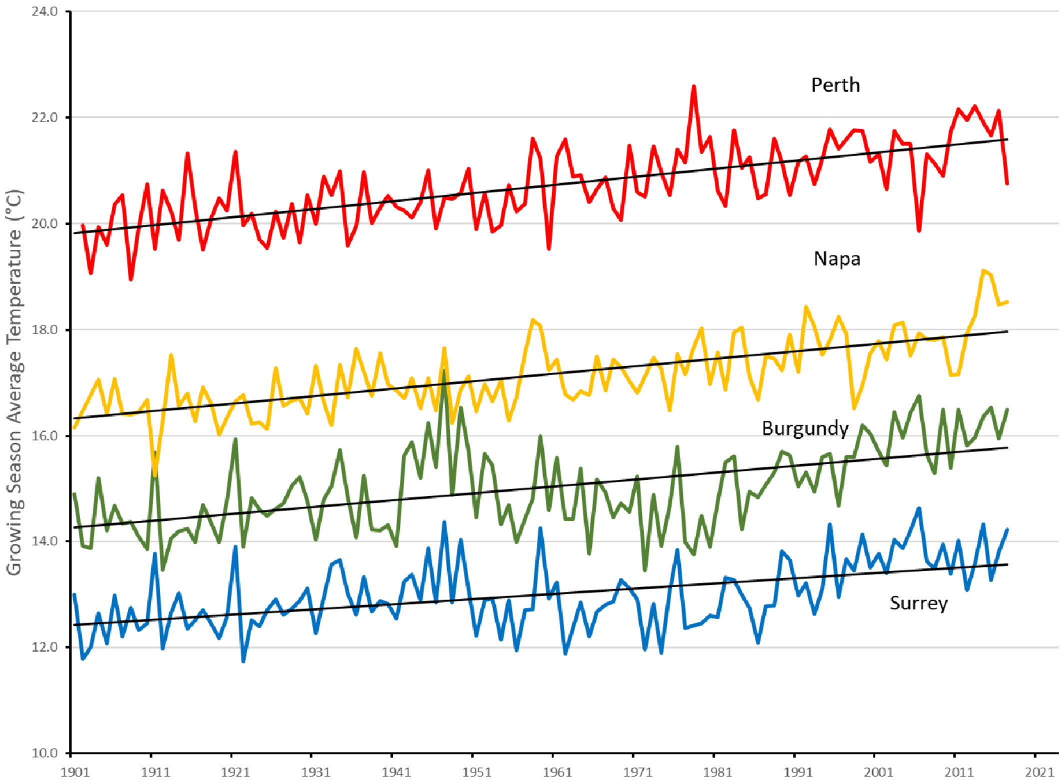

Figure 1: Time series of 1901-2017 growing season average temperatures (April through October in the Northern Hemisphere and October through April in the Southern Hemisphere) for four locations across a range of climates. Additional information provided in Table 1. Data Source: Climatic Research Unit, University of East Anglia, Harris et al. (2014).

Table 1: Trend statistics for 1901-2017 for growing season average temperatures (April through October in the Northern Hemisphere and October through April in the Southern Hemisphere) for 22 wine regions, including the four locations in Figure 1. Note that each time series has a statistically significant trend (α=0.05), the slope is for the period of record (POR), the decadal trend is averaged over the POR, and the POR trend is for the entire time period. Data Source: Climatic Research Unit, University of East Anglia, Harris et al. (2014).

REGION	R^2	SLOPE	TREND: DECADAL	TREND: POR
ADELAIDE, AUSTRALIA	0.18	0.009	0.09	1.0
BORDEAUX, FRANCE	0.41	0.015	0.15	1.8
BURGUNDY, FRANCE	0.29	0.013	0.13	1.5
CURICO, CHILE	0.28	0.008	0.08	1.0
DOURO, PORTUGAL	0.53	0.016	0.16	1.8
LA MANCHA, SPAIN	0.54	0.016	0.16	1.9
MADERA, CALIFORNIA	0.40	0.013	0.13	1.5
MARLBOROUGH, NEW ZEALAND	0.22	0.009	0.09	1.0
MENDOZA, ARGENTINA	0.34	0.011	0.11	1.3
NAPA, CALIFORNIA	0.51	0.014	0.14	1.7
NASA, GREECE	0.14	0.009	0.09	1.0
NIAGARA, CANADA	0.18	0.009	0.09	1.1
PERTH, AUSTRALIA	0.49	0.015	0.15	1.8
PIEDMONT, ITALY	0.41	0.016	0.16	1.8
RIOJA, SPAIN	0.51	0.017	0.17	2.0
SONOMA, CALIFORNIA	0.54	0.015	0.15	1.8
STELLENBOSCH, SOUTH AFRICA	0.49	0.012	0.12	1.4
SURREY, ENGLAND	0.26	0.010	0.10	1.1
TASMANIA, AUSTRALIA	0.43	0.013	0.13	1.5
TUSCANY, ITALY	0.37	0.013	0.13	1.6
WILLAMETTE VALLEY, OREGON	0.16	0.008	0.08	1.0
WALLA WALLA, OREGON/WASHINGTON	0.11	0.007	0.07	0.9

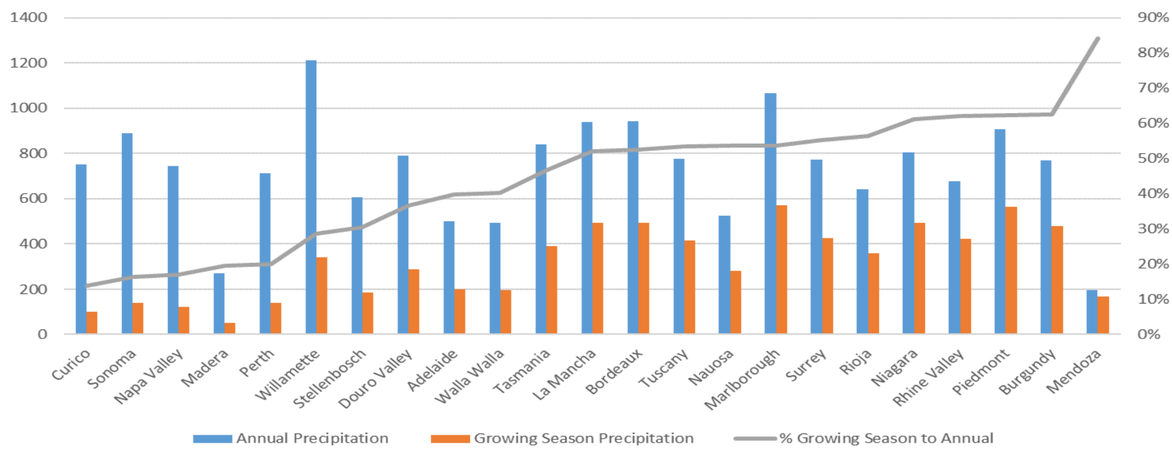

Figure 2: Annual and growing season precipitation (April through October in the Northern Hemisphere and October through April in the Southern Hemisphere) for 22 regions across a range of climates. Additional information on trends in precipitation across annual, growing season, and other seasonal periods provided in Table 2. Data Source: Climatic Research Unit, University of East Anglia, Harris et al. (2014).

Table 2: Trends for 1901-2017 for precipitation (mm) during annual, growing season[1] (April through October in the Northern Hemisphere and October through April in the Southern Hemisphere), winter[2](DJF, JJA), spring[3] (MAM, SON), summer[4] (JJA, DJF), and fall[5] (SON, MAM) periods for 22 wine regions. Note that each time series with a value has a statistically significant trend (α=0.05) over 1901-2017. Data Source: Climatic Research Unit, University of East Anglia, Harris et al. (2014).

REGION	ANNUAL	GROWING SEASON[1]	WINTER[2]	SPRING[3]	SUMMER[4]	FALL[5]
ADELAIDE, AUSTRALIA						
BORDEAUX, FRANCE						
BURGUNDY, FRANCE	80	60	57			
CURICO, CHILE	-198		-107			-74
DOURO, PORTUGAL		72				
LA MANCHA, SPAIN						
MADERA, CALIFORNIA						
MARLBOROUGH, NEW ZEALAND			41			
MENDOZA, ARGENTINA	63	54			31	
NAPA, CALIFORNIA						
NAUOSA, GREECE						
NIAGARA, CANADA	152	115			44	72
PERTH, AUSTRALIA	-177		-131			
PIEDMONT, ITALY						
RIOJA, SPAIN						
SONOMA, CALIFORNIA						
STELLENBOSCH, SOUTH AFRICA	-96			-52		
SURREY, ENGLAND						
TASMANIA, AUSTRALIA						
TUSCANY, ITALY						
WILLAMETTE VALLEY, OREGON				51		
WALLA WALLA VALLEY, OREGON/WASHINGTON	69			40		