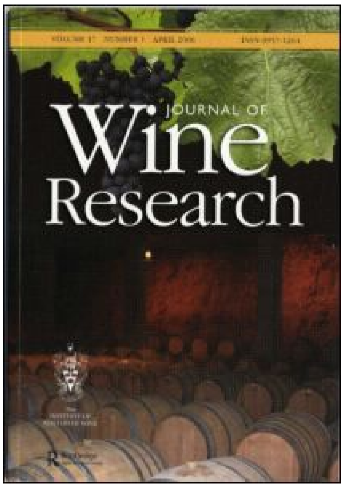

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Climate Induced Historic and Future Changes in Viticulture

HANS R. SCHULTZ and GREGORY V. JONES

ABSTRACT *Grapes are an extremely climate sensitive crop and vines have been cultivated for several thousand years. Over time many grape growing regions have been established, whose specific climatic conditions matched the capacity of certain varieties to produce wines of distinctive character. Through warm and cool periods of the past, climatic boundaries for successful grape growing were traditionally located between the latitudes 30 and 50°N and 30 and 40°S, or encompassing the 12° to 22°C isotherms for the growing season (April–October, October–April). Climate change in the future will likely cause these boundaries to move north and south, respectively. Concomitantly, varietal suitability will be affected and a disruption of historically grown combinations (and identifications) of certain varieties with certain wine regions is likely. The projected rise in temperature will also alter grape composition and the wine styles produced and, along with predicted changes in precipitation amounts and seasonal timing, will challenge grape growing and wine making in the future.*

Climate is a decisive factor for the cultivation of agricultural crops, from the geographical suitability to the effects on yield and quality. Throughout human history, these strong ties determined the cultural and economic development of regions, created local identities and has influenced migration and settlements. In the field of agriculture, these connections have its most intense expressions in the production of grapes and wine. Grapevines have been cultivated for several thousand years and during this long history specific growing regions were established, whose climatic conditions played a decisive role in the formation of specific wine characteristics from certain varieties. Over time, climate parameters (such as temperature) were used to delimit the boundaries of wine regions and to develop legal frameworks that are still present in the current definition of wine regions throughout the European Union, for example (Huglin, 1986). The 'European experience' has been used as a model, in that climatic indices of different European wine regions were applied to 'New World' regions to determine general suitability and the choice of cultivars (Gladstones, 1992).

Climate and Viticulture in the Past

Direct weather records, which in some European wine growing regions often date back to the nineteenth century indicate a warming trend, particular during the latter part of

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the twentieth century (Gladstones, 1992; Jones *et al.*, 2005a). These data match the observed global trend (IPCC, 2007). The history of European viticulture, however, also reflects large variations in the prevailing climatic conditions. In particular, records of grape harvest dates (GHD) from France (Le Roy Ladurie and Baulant, 1980; Chuine *et al.*, 2004) and Switzerland (Pfister, 1992; Meier *et al.*, 2007; Krieger *et al.*, 2010) have been used as a proxy archive for temperature extending from the present to medieval times. Chuine *et al.* (2004) used a process-based phenology model for the grape variety Pinot noir to reconstruct spring and summer temperatures in Burgundy for the period 1370 to 2003. The reconstructed temperature anomalies significantly correlated with other means of climate reconstruction such as tree ring analyses from central France (Chuine *et al.*, 2004). The analysis of the Swiss data set for GHD between 1480 and 2006 confirmed a strong correlation with April to August temperatures (Meier *et al.*, 2007; Krieger *et al.*, 2010). The analyses showed significant warm periods between 1380 and 1420, around 1520 and between 1630 and 1680, which were similar to, or above the temperatures recorded during the 1990s and the beginning of this century (with the exception of 2003) (Chuine *et al.*, 2004). However, some of the underlying assumptions and modeling approaches in that specific study have been strongly criticized (Keenan, 2007).

Harvest dates also reflect other factors than climate, for example, improvements in agricultural technology, planting material, plant protection or changes in consumer preferences. But even considering these developments and based on many historic sources, Gladstones (1992) concluded, that in the high middle ages (twelfth to thirteenth centuries), thus before the time considered in the proxy records analysed by Chuine *et al.* (2004) and Meier *et al.* (2007), average temperature during the growing season (April–October) in Central and Western Europe is likely to have been 1.4°C above those recorded during the 1990s. From both data sets it seems clear, that temperatures after about 1730 until the beginning of the nineteenth century where substantially lower than before (with GHDs being later). There are several more data sets from other regions which confirm the strong correlations between temperature and GHD. Records from Schloß (Château) Johannisberg (since 1782) in the Rheingau region of Germany, or Château Lafite (since 1847) in Bordeaux show earlier GHD during the last 30–40 years (Gladstones, 1992) but both data sets also reflect significant cool periods with late GHD (1820 to about 1900) (Figure 1). From the GHD data sets it seems clear that the trend to earlier harvests is more pronounced at higher latitudes and that the development during the last 25–30 years has been unprecedented (Figure 1). Earlier maturity has also been observed in regions outside of Europe, for example, in the US (Wolfe *et al.*, 2005) and Australia (Petrie and Sadras, 2008).

The extension of grape cultivation in Europe to northern Germany, England and further East to Poland at the beginning of the so-called ‘little ice age’ at the end of the sixteenth century (Pfister, 1988; cited in Gladstones, 1992) is another indication for relative warm temperatures during this period. This is especially true given that many grape varieties still in use today were already cultivated at that time (i.e. Sylvaner, Riesling, Gamay, Pinot noir, Traminer, etc.). The following cool period with severe winter frosts towards the end of the seventeenth century (Pfister, 1992) caused large grape growing areas in Central Europe to be abandoned with a concomitant extension in Southern Europe (Gladstones, 1992). Throughout the following warm and cool phases, the ‘northern limit’ of grape cultivation around the 50th degree latitude was becoming a reference for the geographical extension of wine production, as well as the average January temperature −1°C limit for continental climates in Eastern Europe (Branas *et al.*, 1946).

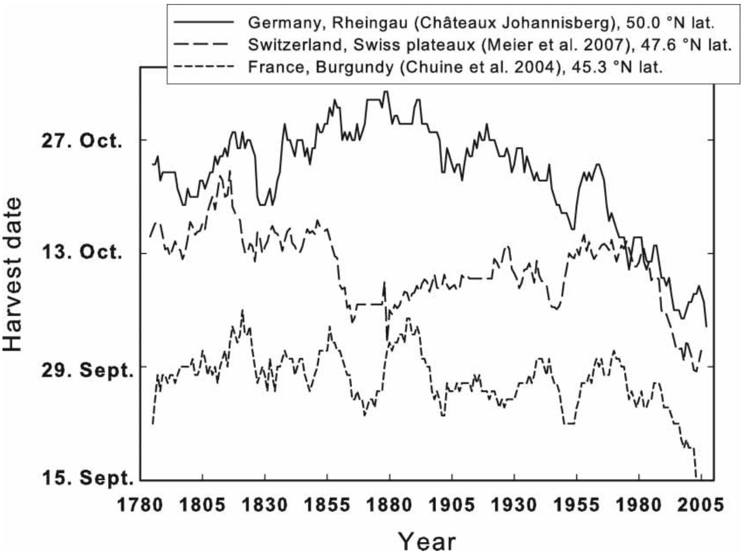

Figure 1. Changes in observed grape harvest dates in three locations since 1780. Schloß (Château) Johannisberg, Rheingau, Germany (50.0°N); Swiss plateaux, Switzerland (Meier *et al.*, 2007, 47.6°N) and Burgundy, France (Chuine *et al.*, 2004, 45.3°N). Lines are 10-year running averages of the original data sets.

Climate and Viticulture Today and in the Future

Traditionally the main grape growing and wine producing areas have been situated between 30° to 50°N and 30° to 40°S (Amerine *et al.*, 1980), although grapes have been grown outside these limits in the tropics for a long time. These latitudes approximate the 10°C and 20°C annual isotherms, which due to the incorporation of winter temperatures do not accurately reflect the real geographical distribution. The current extension of viticulture is best represented by the 12–13°C (lower threshold)—22–24°C (upper threshold) isotherm limits of the average growing season temperature (Figure 2; April–October, Northern Hemisphere; October–April, Southern Hemisphere) (Jones *et al.*, 2005a, 2010; Schultz and Jones, 2008). The 12°C lower limit would be situated just south of London, England (1961–1990 average), whereas the 24°C upper limit would include some tropical areas. For many viticultural regions a warming trend has been observed over the past 50–60 years and has been particularly strong over the past 20 years. An analysis of 27 wine regions worldwide showed that the average winter and summer temperatures have increased by 1.3 and 1.4°C, respectively (Jones *et al.*, 2005a, 2005b) between 1950 and 2000 with a greater increase for regions in the northern hemisphere. Of these regions, 18 showed an increase in temperature variability, which confirms the projections of increased variability by the IPCC (IPCC, 2007). There is evidence that in many regions night temperatures have increased stronger than day temperature (Jones *et al.*, 2005a, 2005b). The current observations in the trends corroborate the projections of the first UN climate report of 1990 (Rahmstorf *et al.*, 2007).

One of the early analyses of the impacts climate change on viticulture, shortly after the release of the first UN state of the climate report in 1990, were conducted by Kenny and Harrison (1992). The work indicated potential shifts and/or expansions in the geography of viticulture regions with parts of Southern Europe predicted to become

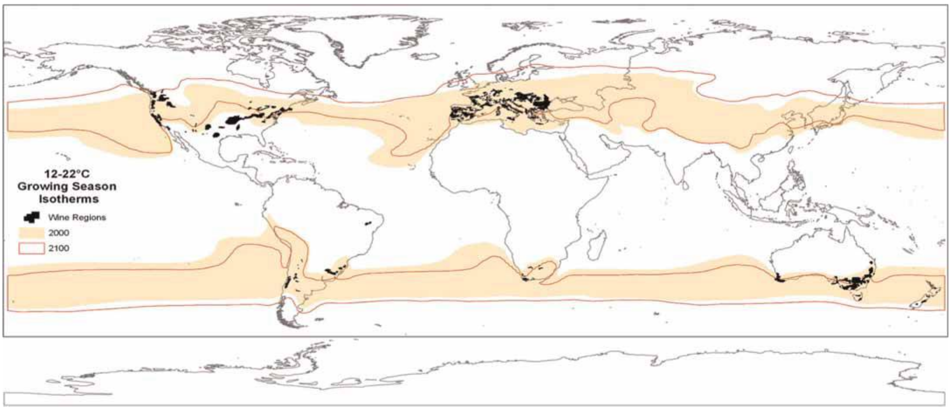

Figure 2. Map of growing season average temperatures (Northern Hemisphere April–October; Southern Hemisphere October–April) derived from observations and model runs from the Community Climate System Model (CCSM). Future projections are driven by the A1B emission scenario (moderate future consumption) for 2100.

too hot to produce high quality wines and northern regions becoming viable once again. These results have largely been proven correct. Other recent research by Jones *et al.* (2005a) examining growing season climates in 27 of the world's top wine producing regions reveals significant changes in each wine region with trends ranging from 0.2°C to 0.6°C per decade for 2000–2049. Overall trends by 2049 average 2°C across all regions.

Depending on the underlying scenario, climate models predict an increase in global temperature of 1.5°C to $>$ 5.0°C by the end of this century (IPCC, 2007). An increase in temperature of this magnitude would substantially alter the geography of wine regions with the potential for relatively large latitudinal shifts in viable viticulture zones (Figure 2). Some increases in suitable area might be seen on the poleward fringe in the Northern Hemisphere (NH), but decreases in area are likely in the Southern Hemisphere (SH) due to the lack of land mass (Figure 2). Within wine regions, spatial shifts are projected to be toward the coast, up in elevation, and to the north (NH) or south (SH). Furthermore, climate variability analyses have shown evidence of increased frequency of extreme events in many regions, while climate models predict a continued increase in variability globally.

Implications for Vine Growth and Wine Composition

Although many individual climate factors play a role in yield formation, grape development and grape composition (i.e. solar radiation, temperature and temperature extremes, precipitation amount and distribution, wind, humidity, etc.), temperature and water supply are among the most important (Coombe, 1987). These are also the two factors most frequently addressed in reflections on the possible effects of climate change on viticulture (Schultz and Stoll, 2010).

In a comprehensive worldwide analysis of long-term time trends in vintage ratings for major wine-producing regions, Jones *et al.* (2005a) showed a sustained increase in vintage quality, possibly resulting from complex combinations of improved winemaking and crop management technologies, and warming trends. Whereas in this analysis a quadratic effect of temperature on wine quality was assumed, with an implicit expectation of quality improvement with warming in cool regions, and a decrease in quality in hotter regions, trends were positive in 25 out of 30 regions, with only one case of a negative, but statistically non-significant trend in quality (Jones *et al.*, 2005a). However, Jones *et al.* (2005a) showed that many of the wine regions may be at or near their optimum growing season temperatures for high quality wine production and further increases will likely place some regions outside their theoretical optimum growing season climate.

In addition, several studies have shown that grapevine phenology has significantly advanced in many wine growing regions in the past (Jones *et al.*, 2005b; Duchene and Schneider, 2005) and will continue to shift forward in time with the main ripening period occurring at much higher temperatures (Webb *et al.*, 2007, 2008). This is likely to affect grape composition, as evidenced by long-term increases in temperature in the past being implicated in altered fruit composition in Europe, North America and Australia (Schultz, 2000; Duchene and Schneider, 2005; Wolfe *et al.*, 2005; Petrie and Sadras, 2008). While many studies have used temperature indices to predict shifts in the varietal spectrum (Kenny and Harrison, 1992; Schultz, 2000; Stock *et al.*, 2005), these approaches do not incorporate possible mitigation strategies through cultivation methods. Several of these strategies aim at retarding ripening in order to shift the maturity timing back to periods with cooler conditions (Stoll *et al.*, 2009) that are more optimum for phenolic ripeness and flavour development.

It is also very likely that different varieties will respond differently to warming. For example, an increase in temperature from 20 to 30°C increased the weight of bunch primordia four-fold in Riesling but Shiraz was unaffected (Dunn, 2005). Shiraz also showed very little response in basic yield components in a 2 to 4°C warming experiment (Sadras and Soar, 2009). In principle, red varieties appear to tolerate warm conditions better than white varieties. In an in-depth analysis of the relationship between vintage quality and the long-term daily mean temperature during the month prior to harvest, Sadras *et al.* (2007a) found contrasting responses for red and white varieties across 24 Australian wine regions. There was a positive correlation of quality ratings and daily mean regional temperature for red but not for white wines, whereas the apparent influence of temperature on vintage variability was strong for white wines but irrelevant for red wines. However, when wine score data were correlated with the average growing season temperature (October to April), there was a negative trend for red and white wines in some of the analyzed regions (Hayman *et al.*, 2009).

Under hot climate conditions red fruit varieties including Cabernet Sauvignon usually achieve sugar concentrations suitable for quality wine making, but often fail to colour appropriately (Iland and Gago, 2002). The relative stability of sugar in comparison to the plasticity of anthocyanins is partly related to the relative ranges of temperature for optimum activity of sugar (18 to 33°C) and pigment producing enzymes (17 to 26°C) (Iland and Gago, 2002; Sadras *et al.*, 2007b). Specifically high temperatures (>30°C) directly after véraison can inhibit anthocyanin formation (Mori *et al.*, 2007). These apparent relationships are valuable information, but we only have a small data base of grape composition data, which seems insufficient to extrapolate to past or future climates in terms of wine quality.

Despite the low plasticity of sugar accumulation, Jones and Davis (2000) found a continuous, albeit not significant, increase in sugar concentration at harvest between 1970 and 2000 for selected vineyards in Bordeaux. Acidity, however, may be a better proxy for changes in grape composition, since both the pre-véraison formation of malic acid and its degradation after véraison are highly temperature sensitive

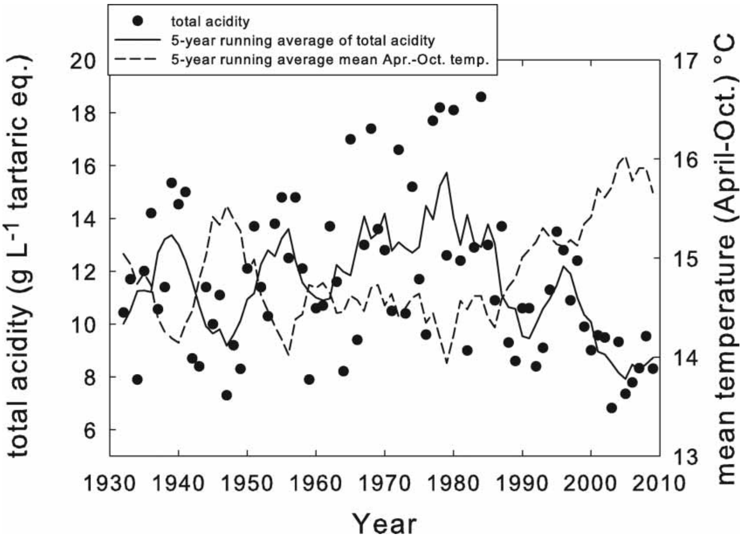

Figure 3. Total acidity data at harvest for Schloß Johannisberg since 1932. Data are means of eight to 125 individual values for different Riesling vineyards around Johannisberg/Geisenheim for any particular year. Seven years of missing data were replaced by data from vineyards of the Geisenheim Research Centre in close proximity to Schloß Johannisberg. Lines are five-year running averages for total acidity and April to October average temperatures.

(Kliewer, 1973; Ruffner *et al.*, 1984), thus malic acid shows much more plasticity than sugar. We therefore exploited a relatively unique data set from Schloß Johannisberg in the Rheingau region, Germany, with yield, sugar concentration and total acidity (malic and tartaric acid) data going back to at least 1932. Schloß Johannisberg has exclusively cultivated the variety Riesling since 1720. The data shown in Figure 3 are averages across all individual vineyards of any particular year at time of harvest (between a minimum of eight to a maximum of 125 values per year). There is a clear negative correlation between total acidity and seasonal average temperature (Figure 3). In particular, the strong decrease in acidity over the past 20 years or so was concomitant to a strong increase in growing season temperature (Figure 3). This correlation was better than with any other temperature data of individual months or parts of the growing season (data not shown). Since tartaric acid is largely unaffected by temperature, the variation in acidity concentration is related to changes in malic acid (Ruffner, 1982). These data and their correlation with temperature confirm, that total acidity is a good proxy for seasonal temperature and that it may be possible to model its development using various climate scenarios.

Conclusions

Climate change has the potential to greatly impact nearly every form of agriculture. However, history has shown that the narrow climatic zones for growing winegrapes are especially prone to variations in climate and long term climate change. While the observed warming over the last 50 years appears to have mostly benefited the quality of wine grown worldwide, projections of future warming at the global, continental and wine-region scale will likely have both beneficial and detrimental impacts through opening new areas to viticulture and increasing viability, or severely challenging the ability to adequately grow grapes and produce wine.

The spectrum of vineyard sites, climatic conditions, soil types and varieties across the world's grape growing areas is so large, that a general type of adaptive strategy is not possible. In many cases, the balance between vineyard site, climate, soil, variety and the applied cultivation measures, which has developed sometimes over centuries, will be perturbed or even completely altered.

The simplest deduction would be that the varietal spectrum would change substantially since the suitability for the cultivation of a given cultivar is largely temperature driven (Huglin, 1986; Gladstones, 1992, 2004). However, in many cases only the lower threshold of varietal suitability has been well defined (Huglin, 1986; Jones *et al.*, 2005a), while the upper suitability threshold of many varieties remains uncertain (Hayman *et al.*, 2009). Since very often the image of a wine growing region is determined by one or a limited number of cultivars (e.g. Riesling for the Mosel and Rheingau regions in Germany; Pinot noir and Chardonnay for Burgundy, Cabernet Franc, Cabernet Sauvignon, Merlot for Bordeaux, France; Nebbiolo for the Piedmont region of Italy) changing these cultivars may not be the immediate appropriate solution. Additionally, within Europe, the use of specific varieties is often regulated by law, which may become problematic in light of future climatic developments.

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