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Global warming and wine quality: are we close to the tipping point?

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ABSTRACT

Wine grapes are one of the most lucrative crops in the world and this value is founded heavily on traditional winegrowing regions established over hundreds of years. These regions are now experiencing marked changes in climate. People speculate that global warming could reshape the distribution of premium wine-growing regions, pushing regions to higher latitudes and elevations with cooler temperatures. A major redistribution of this kind would be catastrophic for numerous regional economies. Here we examine relationships between warming, fruit ripening, and wine quality in two renowned red wine regions; Napa Valley, California, USA, and Bordeaux, France. We show that both regions have warmed substantially over the past 60+ years and that until now this warming has contributed to increases in the average wine quality. However, ripening relationships revealed that we are reaching a plateau and raise concerns that we may be approaching a tipping point in traditional wine-growing regions.

KEYWORDS

climate change, ripening, Bordeaux, Napa Valley

Supplementary data can be downloaded through: https://oeno-one.eu/article/view/4774

INTRODUCTION

Wine grape growing is one of the most lucrative and culturally important cropping systems in the world (Alston and Sambucci, 2019). The industry was founded upon specific region-climate-cultivar rapports that have a strong historical context, and there is now growing concern that global warming could reshape these regions, pushing them to higher latitudes and elevations in search of cooler temperatures (Hannah *et al.,* 2013; Schultz and Jones, 2010). The logic underlying these predicted regional shifts relies on the observation that specific wine grape cultivars each have an optimum temperature range within which they can reliably produce high-quality wines that have commercial acceptance (Keller, 2010). Thus, as regional climates warm outside of these optimum ranges, wine quality would decrease. For a region to survive it would have to adapt, presumably by changing management strategies to maintain fruit and wine quality and/or changing cultivars to those better suited to the new, warmer climate norm (van Leeuwen *et al.,* 2019). A major redistribution of wine-growing regions would be catastrophic for numerous regional economies. But even changing cultivars could be extremely disruptive since they bring about the distinctiveness of the wines that define a region's identity.

Optimum temperature ranges are delimited by a lower threshold necessary to ripen the fruit and an upper threshold that would lead to over-ripe (or even damaged) fruit (Coombe, 1987). What constitutes optimum ripeness and quality is somewhat subjective and depends on the particular wine style and target market. Despite the variability of style and taste, ripe fruit must include sufficient levels of sugar (that will be transformed into alcohol via fermentation) and secondary metabolites that contribute to the wine sensory profile (i.e., colour, aromatics, flavour, mouthfeel). In fact, ripening targets are often defined by grape sugar concentration (Coombe *et al.,* 1980). This is because the accumulation of sugar and numerous quality-related secondary metabolites are strongly correlated during ripening, although they may be uncoupled late in ripening (Martínez-Lüscher *et al.,* 2017; Sun *et al.,* 2017) and/or by particular environmental factors (Torres *et al.,* 2021).

Cultivar specific temperature ranges were suggested as primary criteria used to predict viticultural suitability under future climate change scenarios (Hannah *et al.,* 2013; Jones *et al.,* 2012; Morales-Castilla *et al.,* 2020; Parker *et al.,* 2020). Suitability studies have defined the current zeitgeist in the wine world: that climate change will determine regional "winners" where temperature increases above lower thresholds will allow for increased quality winegrape production, and "losers" where temperature increases above upper thresholds will make quality winegrape production impossible (or unsustainable). One example of a current winner is the United Kingdom which is rapidly expanding its winegrape production and reputability (Nesbitt *et al.,* 2016). In well-established regions, anecdotal evidence regarding the impact (positive or negative) of climate change on ripening and wine quality is mixed (Adelsheim *et al.,* 2016), and how much warming is too much for established wine regions remains an open question, as the majority of the world's vineyards are planted in warm to hot climate regions.

Here we examined the relationships between warming, ripening, and wine quality in two of the world's top red wine regions, Napa Valley in California, USA and Bordeaux, France. We showed that both regions have warmed substantially over the past 60+ years and that until now this warming has resulted in increases in the average wine quality. However, ripening relationships reveal that we are reaching a plateau and raise concerns that we may be approaching a tipping point.

MATERIALS AND METHODS

1. Historical climate and phenology data for Napa and Bordeaux

Historical climate data were curated from the United States National Oceanic and Atmospheric Administration database for Napa, CA USA and the Meteo France database for Bordeaux, France. The growing degree days were calculated using 10 °C as the base temperature in each year with no upper limit. The growing season was defined as the period from the 1st of April to through 30th of October. Heat spike days were defined as those days with a maximum temperature greater than 34 °C. Phenology intervals between veraison and harvest were calculated for the years available using data from the Napa Valley Vintners (https://napavintners.com) Harvest Reports and Chevet *et al.* (2011) for Bordeaux, France.

2. Sugar concentrations at harvest and wine quality ratings

The harvest sugar concentrations were acquired from the California Grape Crush Report database (www.cdfa.com) for Napa, CA, USA, and from an average of Pauillac 1 & 2 from Soyer and Chevet (2007) for Bordeaux, France. The Napa, CA, USA, wine quality ratings were acquired from compiling Wine Spectator (www.winespectator.com) ratings for "Cabernet-Sauvignon" and "Merlot" wines from California from over 1900 wines and taking the mean rating per year. For Bordeaux, France wine quality ratings were acquired by taking the mean of three different vintage quality sources: Tastet & Lawton (presented in Soyer and Chevet, 2007), *Le Guide Hachette des Vins 2020* ("*Bordeaux rouge*" category), and Cellar Insider (www.thewinecellarinsider.com).

3. Sugar and anthocyanin analysis in Napa and Sonoma

Must sugar and skin anthocyanin concentrations in two vineyards in Napa and Sonoma County, California, USA, were measured four times each year. Briefly, 75 berries from 48 plants at each vineyard, spaced 30 m × 30 m equidistantly were sampled at ~12, 16, 21 and 25 % total soluble solids. 50 berries were crushed by hand and filtered to obtain must. A digital refractometer (Palette PR-32, Atago Tokyo, Japan) was then used to measure total soluble solids as described elsewhere (Yu *et al.,* 2020). Twenty randomly chosen berries from the 75 berries set were used for anthocyanin measurement. The berry skins were peeled by hand using a scalpel and freeze-dried (Centrivap, Labconco, Kansas City, MO, USA). Dried skins were pulverised in a ball mill (MM400, Retsch, Mammelzen, Germany). A solution of MeOH:H_2O:7 M HCl (70:29:1) was added to 50 mg of freeze-dried, pulverised skin to quantify anthocyanins and allowed to extract overnight at 4 °C. Following extraction, samples were centrifuged at 14,000 rpm for 10 minutes and supernatants filtered (0.45 µm; VWR, Seattle, WA, USA) into HPLC vials and analysed. An HPLC-DAD (1260 series, Agilent, Santa Clara, CA) equipped with a degasser, quaternary pump, thermostatted column compartment and an auto-injector connected to a diode array detector was used to analyse the anthocyanins. Mobile phase elution gradient, anthocyanin quantification followed previously established procedures (Martínez-Lüscher *et al.,* 2019) with a reversed-phase C18 column LiChrosphere® 100, 250 × 4 mm with a 5 µm particle size and a 4 mm guard column of the same material (Agilent Technologies, Santa Clara, CA, USA). The mobile phase flow rate was 0.5 mL min^{-1}, and two mobile phases were used, which included solvent A = 5.5 % aqueous formic acid; solvent B = 5.5 % formic acid in acetonitrile. The HPLC flow gradient started with 91.5 % A with 8.5 % B, 87 % A with 13 % B at 25 min, 82 % A with 18 % B at 35 min, 62 % A with 38 % B at 70 mins, 50 % A with 50 % B at 70.01 min, 30 % A with 70 % B at 75 min, 91.5 % A with 8.5 % B from 75.01 min to 91 min. The column temperature was maintained at 25 °C. Detection of anthocyanins was carried out by the diode array detector at 520 nm, respectively. A computer workstation with Agilent OpenLAB (Chemstation edition, version A.02.10) was used for chromatographic analysis.

4. Data analysis, visualisation, and statistics

All data analysis, visualisation and statistics were performed using R software (http://www.R-project.org) and associated packages. Regression analyses for all variables were carried out using either a linear or a second-order polynomial model as specified in the presentation of the results.

RESULTS AND DISCUSSION

1. Napa, Bordeaux, and the 1980s global regime shift

Several different temperature metrics from 1950–2020 in Napa and Bordeaux all support the same conclusion; temperatures have increased significantly (Figure 1, Supplemental Figure S1). Annual growing degree day (GDD) increases are strikingly similar between the two regions and increased markedly starting in the early 1980s (Figure 1A). This coincides with the 1980s global regime shift and suggests global viticulture similarly reflected the major perturbations to earth systems observed during this period (Reid *et al.,* 2016). Both regions have moved through several "Winkler Regions" (i.e., climatic zones delimited by GDD that define optimal cultivar/climate rapport (Amerine and Winkler, 1944) since the late 1970s, moving from Region II, through Region III, and into Region IV in just under 30 years (Figure 1A). The same increases in temperature are observed in average growing season temperature (Supplemental Figure S1A). Observations of the average growing season maximum temperature, as well as the frequency of "heat spikes" (defined as a day with a max. temperature > 34 °C), both, showed significant increases as well (Figure 1B, 1C). Although there have been no apparent long-term changes in precipitation in the regions, in Bordeaux increasing maximum growing season temperature

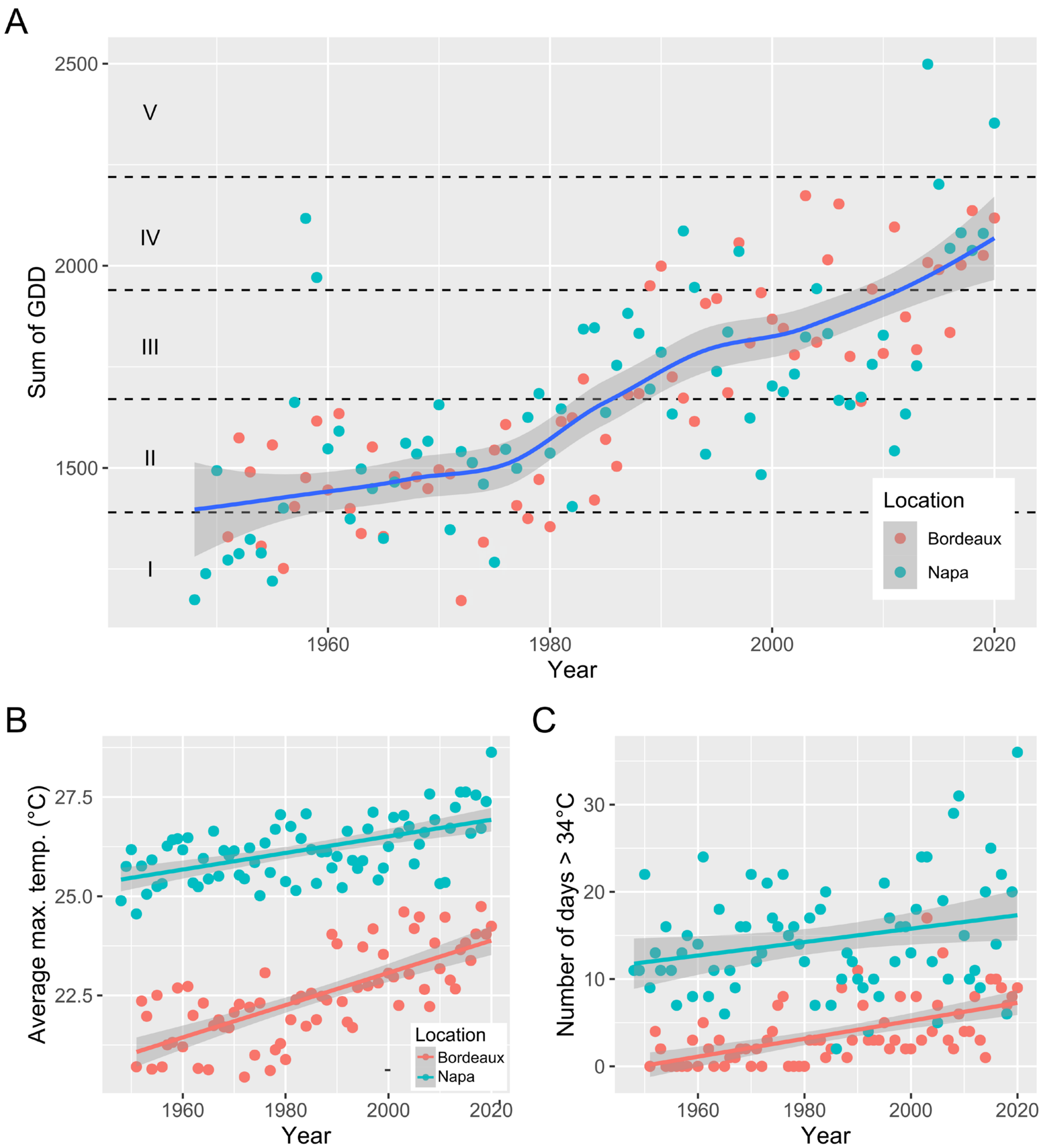

FIGURE 1. Long-term evolution of different temperature metrics in Napa and Bordeaux.

A) Increases in the cumulated annual growing degree days (GDD) over time in Napa and Bordeaux ($P < 0.0001$). The trend in GDD in both regions is shown by the blue line (lœss smoothing) with the 95 % confidence intervals shown with grey shading. Winkler regions are delimited with dashed horizontal lines and are labelled by Roman numerals from I to V corresponding from the coolest to warmest region designations.

B) Historical changes in the average growing season (from 1st of April until 31th of October) maximum temperature. Linear regressions and corresponding 95 % confidence intervals are shown (Napa; $r^2 = 0.32$, $P < 0.0001$, Bordeaux; $r^2 = 0.54$, $P < 0.0001$).

C) Historical changes in the number of heat spike days, defined as a day with maximum temperature > 34 °C, during the growing season. Linear regressions and corresponding 95 % confidence intervals are shown (Napa; $r^2 = 0.07$, $P < 0.05$, Bordeaux; $r^2 = 0.33$, $P < 0.0001$).

is weakly correlated with decreasing precipitation (Supplemental Figure S1). The speed of these temperature changes is alarming and raises a serious question; if similar regime shifts occur in the future can viticultural cropping systems adapt fast enough?

2. Increased temperature and riper fruit

One of the most immediate concerns for the wine industry is that higher temperatures could negatively impact fruit composition and wine quality (Torres *et al.,* 2020). Coinciding with the abrupt temperature increases in the 1980s sugar concentrations in Napa and Bordeaux began to increase significantly and these increases have continued (Figure 2A). Interpretations of these changes need to be made with caution since harvest is a human decision, and thus changes do not necessarily reflect a climate-driven cause. If growers simply decided to harvest fruit later (and thus at higher sugar concentrations) then we would expect the interval between the onset of ripening (i.e., veraison) and harvest to increase. This has not been the case in Bordeaux, although in Napa there is a (non-significant) suggestion that harvest decisions may have played some role (Supplemental Figure S2). A longer growing season may allow growers to decide exactly when to harvest which could be an advantage. The relationship between annual GDD and sugar concentration is highly significant (Figure 2B). This is consistent with the published literature supporting temperature's causative role in the observed sugar increases (Pastore *et al.,* 2017) resulting in part from accelerated ripening (Torres *et al.,* 2020) and/or increased fruit dehydration (Martínez-Lüscher *et al.,* 2020). Higher sugar concentrations at harvest mean riper fruit (Brillante *et al.,* 2017) and higher alcohol wines of a different style and sensory profile. Thus far these different sensory profiles have resulted in greater consumer acceptance in the marketplace (Bindon *et al.,* 2013).

3. Wine quality and the tipping point

The observed increases in temperature in the two regions are positively correlated with the average vintage quality rating (Figure 3) although the correlation is much weaker for Napa, as it was comparatively warmer than Bordeaux prior to the 1980s global shift.

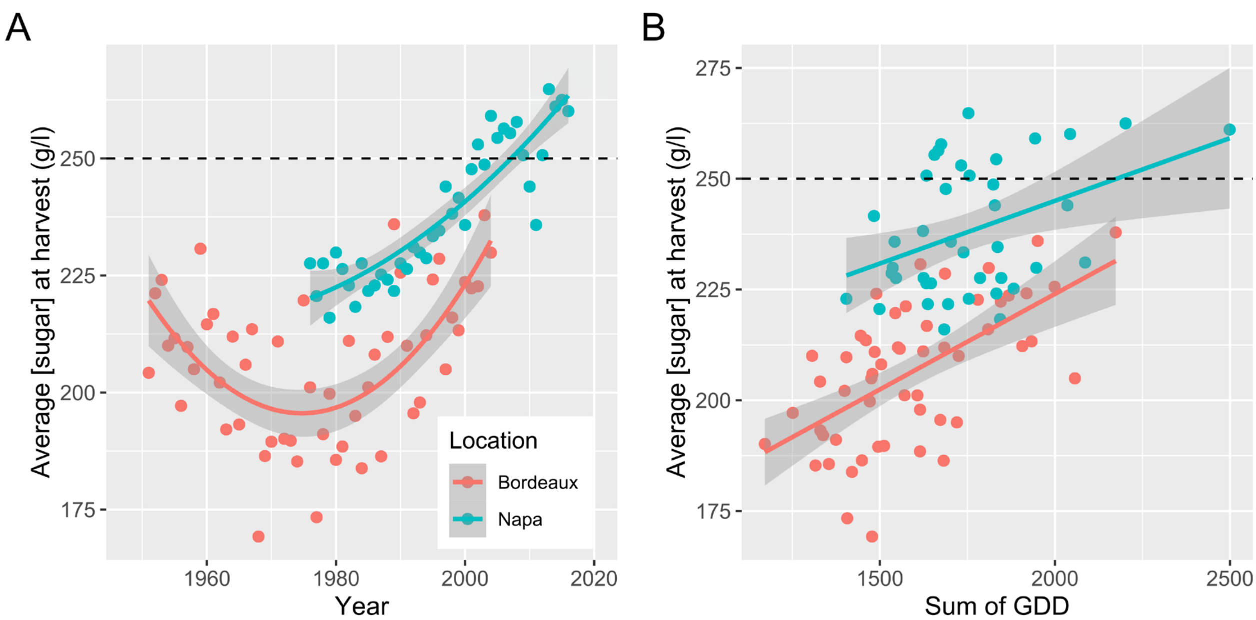

FIGURE 2. Evolution of average sugar concentrations at harvest in Napa and Bordeaux over time, and their relationships with temperature.

A) Historical changes in average sugar concentrations at harvest in Napa (based on Cabernet-Sauvignon) and Bordeaux (based on Medoc red blend alcohol levels from Chevet and Soyer, 2009). Polynomial regressions and corresponding 95 % confidence intervals are shown (Napa; $r^2 = 0.81$, $P < 0.0001$, Bordeaux; $r^2 = 0.41$, $P < 0.0001$).

B) The relationship between cumulated annual growing degree days (GDD) and average sugar concentrations at harvest. The horizontal black dashed lines are presented as a reference for the sugar levels above which there is a marked loss of berry colour (i.e., anthocyanins) from Figure 4. Linear regressions and corresponding 95 % confidence intervals are shown (Napa; $r^2 = 0.16$, $P < 0.009$, Bordeaux; $r^2 = 0.36$, $P < 0.0001$).

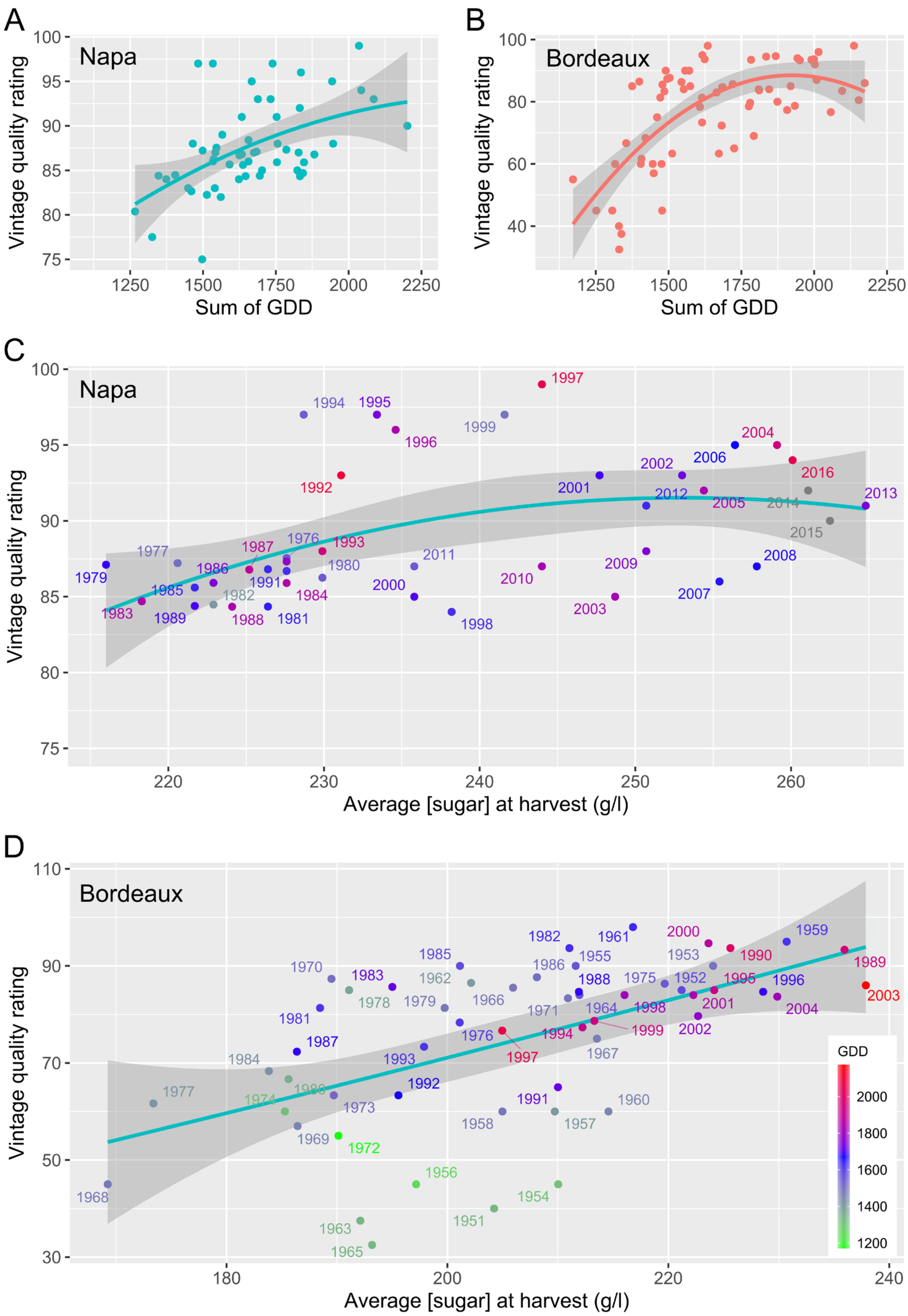

FIGURE 3. The relationships between average vintage quality ratings, temperature, and fruit sugar concentrations at harvest in Napa (1961–2016) and Bordeaux (1950–2018).

Polynomial regressions and corresponding 95 % confidence intervals are shown for all relationships.

A & B) The relationship between cumulated annual GDD and vintage quality in Napa and Bordeaux (Napa; $r^2 = 0.27$, $P < 0.0001$, Bordeaux; $r^2 = 0.48$, $P < 0.0001$).

C & D) The relationship between average sugar concentrations at harvest and vintage quality in Bordeaux and Napa (Napa; $r^2 = 0.24$, $P < 0.005$, Bordeaux; $r^2 = 0.32$, $P < 0.0001$). Points are coloured according to the accumulated GDD for the giving vintage (legend shown in panel D).

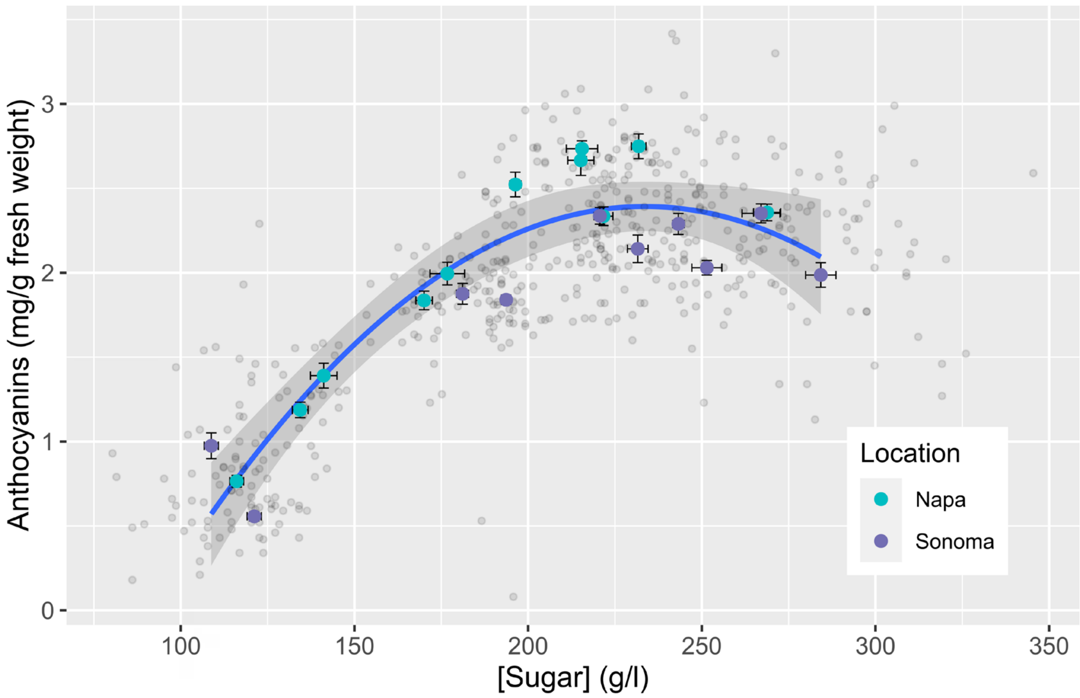

FIGURE 4. Relationships berry sugar and anthocyanin concentration in Cabernet-Sauvignon grown in Napa and Sonoma.

The data were taken across five vintages (see Supplemental Figure S3), and all data are presented as grey points. The coloured points represent averages of berries sampled on the same day (3–5 days per vintage, error bars represent ± standard error). Polynomial regressions and corresponding 95 % confidence intervals are shown ($r^2 = 0.86$, $P < 0.0001$).

High vintage ratings occurred across almost the full range of GDD (except for the coldest years), and higher temperatures significantly decreased the likelihood of a poorer vintage. Importantly, even the warmest vintages do not show any significant decrease in quality. A similar positive relationship exists between fruit sugar concentrations at harvest and quality (Figure 3C, 3D). The idea of a lower temperature threshold is clearly evidenced in Bordeaux where the coolest vintages mostly diverge for the relationship between sugar and quality (Figure 3D). It is important to stress that quality ratings are subjective and likely differ between the two regions, thus we are not concluding that there is strict causality between these factors. In addition, both regions have had some high-quality vintages at lower sugar concentrations suggesting that high sugar is not tantamount to high quality. What is true is that to date increased warming and riper fruit have not been associated with any loss of wine quality. Instead, higher temperatures have made wine quality more consistently good, perhaps due in part to evolving consumers preference for more ripe flavours with subdued, vegetative aromas and tannin profiles (Bindon *et al.,* 2014). However, if we assume that warming will continue, where is the tipping point?

It is well-established that high temperature can have deleterious effects on wine grape composition that include decreases in anthocyanins (the pigmented molecules that give red wine its colour) and other quality-related molecules (e.g., other phenolics, volatile aromas) (Martínez-Lüscher *et al.,* 2020; Sadras and Moran, 2012; Torres *et al.,* 2020, 2021). Examining the relationship between sugar and anthocyanin accumulation in Cabernet-Sauvignon across five vintages in California we see that anthocyanin showed a clear maximum beyond which riper fruit (as defined by sugar concentration) were associated with a loss of colour (Figure 4, Supplemental Figure S3). At sugar levels above 200–225 g/l (~21–22 °Brix) anthocyanins no longer accumulated and became decoupled from sugar accumulation (Martínez-Lüscher *et al.,* 2017; Martínez-Lüscher *et al.,* 2020; Torres *et al.,* 2020; Torres *et al.,* 2021). Above 250 g/l (~25 °Brix) of sugar, colour was lost to some extent (Torres *et al.,* 2020). Anthocyanins are just one of many important quality-related compounds for red wines, but skin flavonols also undergo a marked degradation above similar thresholds (Martínez-Lüscher *et al.,* 2019). The degradation of these quality-related compounds and the observed plateaus of wine quality ratings suggests there can be too much of a good thing.

CONCLUSIONS

Here we show that two of the world's top wine regions, Napa and Bordeaux, are warming at a remarkable rate and their pattern of warming reflects global regime shifts observed across other earth systems during the same period. Growers, scientists, and wine professionals all speculate that these drastic temperature increases will negatively impact fruit and wine quality at some point; however, our analyses here suggest that setting hard temperature thresholds for optimal berry composition and wine quality is difficult. Case in point, a past study using data through 1999 predicted an optimal average growing season temperature of 17.3 °C for Bordeaux (Jones *et al.,* 2005). However, Bordeaux surpassed that barrier more than a decade ago (Supplementary Figure S1A). Fruit-based metrics such as the sugar-phenolic dynamics presented here and/or specific secondary metabolites (e.g., kaemferol) may be better indicators of losses in fruit quality associated with warming (Martínez-Lüscher *et al.,* 2019). In Napa and Bordeaux viticulture has successfully adapted to a drastically changing climate thus far, but fruit-based metrics raise concerns that we are approaching a tipping point.

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