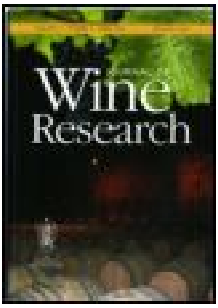

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Climate and Bordeaux wine quality: identifying the key factors that differentiate vintages based on consensus rankings

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The climate of Bordeaux, France, was examined to determine if climatic factors can distinguish between consensus vintage rankings, developed using eight ratings sources, of red and sweet white wines from 1961 to 2009. Climate variables were computed for the growing season and average plant phenological stages and were compared between the 10 highest and lowest ranked vintages. Good vintages exhibited higher heat accumulation during the growing season and a general lack of rainfall, particularly during veraison. Most climate factors were consistent for both red and sweet white wines. Mean maximum temperature during the growing season was an important discriminator between good and poor vintages for both reds and whites, although sweet white wines were also affected by growing season precipitation and temperatures during the vine's dormant period. In general, consensus vintage quality is consistent between reds and whites (Spearman's $\rho = 0.66$, $p < 0.05$), but the primary factor that distinguishes large red vs. white ranking differences is precipitation during the bloom period – when late May–June precipitation is lacking, sweet whites in Bordeaux tend to outperform reds. The information on key climatic factors found in this study can foster appropriate within-season management practices in the vineyard, provide purchasing insights for the wine futures markets in Bordeaux, and focus climate change studies to those climate variables that have the most impact on wine quality.

Keywords: Bordeaux; climate; consensus rankings; grape phenology; viticulture

Introduction

High-quality wine has been produced in the region of Bordeaux, France, for centuries. This excellence can be attributed to the expertise of vintners and a long viticultural history, as well as an ideal climate for growing quality winegrapes. Most of the interannual variability in the overall quality of wine across Bordeaux is related to climate (van Leeuwen et al., 2004). A large number of climatic variables have been linked to vintage quality, and the importance of these variables varies depending on the phenological stage of the plant (Jones & Davis, 2000). In general, wine quality benefits from a long frost-free season, plenty of insolation (Ashenfelter, Ashmore, & Lalonde, 1995), and both a long hang time and a lack of precipitation prior to harvest to concentrate sugars and develop flavours (Jones & Storchmann, 2001; van Leeuwen et al., 2009). However, to date no study has specifically determined those climatic factors that are critical to differentiating overall vintage quality in Bordeaux. A better understanding of climate's role in

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wine quality in Bordeaux could lead to enhanced grower/producer management of the vine and its fruit, and the use of more exact climate metrics could provide economists with better tools to assess wine market pricing and wine aging potential (Ashenfelter, 2008). In addition, the development of these metrics would offer tools to better assess impacts to wine quality in the context of climate change (Jones, White, Cooper, & Storchmann, 2005b).

Most research on the effect of climate on wine quality has used the price of a bottle of wine as a gauge of the overall quality (Ashenfelter et al., 1995; Jones & Storchmann, 2001). In this study, we use a consensus ranking that provides an overall evaluation of each vintage for the entire region of Bordeaux (Borges, Corte-Real, Cabral, & Jones, 2012). Consensus rankings use numerous rating agencies that often employ different numerical scales (e.g. 0–5, 0–20, 0–100, etc.) and have non-equivalent values (e.g. a '92' often implies something different on two different ratings) to establish the 'consensus' ranks of the suite of agencies. Although there tends to be a general agreement on the overall rank of each vintage between wine reviewers (Jones & Goodrich, 2008), by using consensus rankings rather than ratings from individual sources, the potential for biases in ratings can be reduced (Borges et al., 2012).

With respect to climate, previous research for Bordeaux has determined that cool, wet winters and springs followed by warm, dry summers are key factors in the development of a high-quality wine (Ashenfelter, 2008; Jones & Davis, 2000; Jones & Storchmann, 2001). In addition, a high diurnal temperature range (DTR) during the maturation periods typically results in full development of flavours and thus a better vintage (Gladstones, 1992), whereas rain during the veraison and ripening periods dilutes the berries, resulting in lower quality wines (Jones & Davis, 2000; Jones & Storchmann, 2001). Although some research found no significant connection between average daily sunshine hours and vintage quality (van Leeuwen et al., 2004), other results determined that increased insolation during the bloom and veraison periods resulted in an earlier harvest that often correlates with a higher quality vintage (Jones & Davis, 2000; Jones & Storchmann, 2001). Two commonly used variables that measure the accumulated heat over the growing season are growing degree-days (GDD) and the Huglin Index (HI) – both have been used along with other temperature indices to define a region's potential for viticulture (Jones, Duff, Hall, & Myers, 2010; van Leeuwen et al., 2004). The minimum HI necessary for complete ripening varies between grape varieties, from 1700 for sauvignon blanc to 1900 for cabernet sauvignon (Huglin, 1978).

Our goals in this research are to determine the key climatic factors, derived for the entire growing season and for critical phenological stages, which distinguish between high- and low-ranked vintages for both red and white wines in Bordeaux, France. Based upon past research, we hypothesize that high-quality vintages are linked to a cool, wet winter during vine dormancy, warmer than normal growing seasons with high heat accumulation (GDD and/or HI) and below normal precipitation, and high sunshine levels in the later developmental periods. However, because many of the potential predictor variables are correlated, it is likely that only a few climatic factors are critical in determining overall vintage quality. Furthermore, some of these factors may differ between red and white wines.

Data

Daily climatological data were obtained for Mérignac, the main weather station for the Bordeaux region. The data span the 1949–2010 time period and have been used for numerous studies in the region (Jones & Davis, 2000; Jones et al., 2005a; Lecocq & Visser, 2006; Tonietto & Carbonneau, 2004). Observations include maximum, minimum, and average temperature, precipitation amount, daily hours of insolation (direct sunshine), mean wind speed, and station pressure (SP). Although having more stations could be useful, Lecocq and Visser (2006) showed that the variation in weather over the Bordeaux region is small enough that more detailed data from multiple stations or for each specific vineyard would not significantly enhance the robustness of the analysis.

Consensus wine rankings were determined for both red and white wines by combining the rankings of eight different sources: Andy Bassin, Broadbent, Decanter, Sotheby's, Vintage.com, Wine Advocate, Wine Enthusiast, and Wine Spectator (Table 1). These rankings reflect the overall 'consensus' between the eight rating agencies/individuals and were developed using the method of Borges et al. (2012). The consensus rankings for Bordeaux cover red wine vintages from 1961 to 2009 and white wine vintages from 1967 to 2009. The white wine rankings emphasize sweet white wines which are typically from the Sauternes and Barsac regions in Bordeaux. White winegrapes for these wines also require good climatic conditions during the growing period, but are exposed to *Botrytis cinerea* (also known as 'noble rot') during the later stages of ripening, which causes the grapes to become partially dehydrated and results in concentrated and distinctively flavoured wines.

Methods

Derived climate variables

The daily raw weather data are reorganized into periods that coincide with average phenological stages of Bordeaux grapevines (Jones & Davis, 2000): dormancy (1 November of the previous year through 31 March of the year in question), growing season (1 April–31 October), bud break (15 March–15 April), bloom (25 May–20 June), veraison (5 August–5 September), and ripening (1–30 September).

The base weather parameters are used to calculate additional indices that are commonly used to assess the growth and maturation of grapevines (Jones et al., 2010). One such parameter, HI, is calculated using the equation:

$$\mathrm{HI} = \sum_{i=1}^{n} \max\left[\frac{(T_{\mathrm{avg}} - 10°\mathrm{C}) + (T_{\mathrm{max}} - 10°\mathrm{C})}{2}, 0\right] \times d, \tag{1}$$

where T_{avg} and T_{max} are the daily average and maximum temperature (in °C), respectively. The latitude correction, d, takes into account the changes in daylight ranging from 34° to 65° latitude, beginning with a value of 1.0 at 34° and increasing as latitude increases (Jones et al., 2010). As Huglin (1978) varied d between 1.02 and 1.06 between the latitudes of 40° and 50°, we selected a value of 1.05 for Bordeaux (latitude 44.8°N). By definition, the HI is set to zero when the value becomes negative. The HI is calculated for the period from April through September, as is commonly done with the index (Jones et al., 2010). A related parameter, GDD, is calculated as

$$\mathrm{GDD} = \sum_{i=1}^{n} \max\left[\frac{(T_{\mathrm{max}} - T_{\mathrm{min}})}{2} - 10°\mathrm{C}, 0\right]. \tag{2}$$

Daily values of GDD are summed over the time period from April through October, which is one more month than the HI but is consistent with the standard GDD calculation, and all negative values were set to zero. The daily DTR is calculated using the following equation:

$$\mathrm{DTR} = T_{\mathrm{max}} - T_{\mathrm{min}}. \tag{3}$$

Daily precipitation is summed over the various phenological periods, and the number of days with measurable precipitation, defined as any day with precipitation greater than 0.1 mm, is

Table 1. Consensus ranking (ordered from best to worst) of Bordeaux red wine vintages (1961–2009), columns 1–2; and sweet white wine vintages (1967–2009), columns 3–4.

Red		White				
Year	Rank	Year	Rank	Year	Red	White
1961	1	1967	1	1961	1	
2009	1	1990	1	1962	21	
2000	3	2001	1	1963	44	
1982	4	2009	4	1964	35	
2005	5	1988	5	1965	44	
1990	6	1989	5	1966	18	
1989	7	2005	7	1967	36	1
1995	8	2007	8	1968	43	40
1986	9	1983	9	1969	47	36
1985	10	2003	10	1970	12	23
2003	11	1975	11	1971	29	26
2008	12	1986	11	1972	49	42
1970	12	1997	13	1973	39	33
1996	14	1999	14	1974	48	41
2001	14	2006	14	1975	20	11
1988	16	1976	16	1976	34	16
2004	16	1995	16	1977	46	43
1998	18	2002	16	1978	25	24
1966	18	1996	19	1979	27	30
1975	20	1998	20	1980	40	29
1962	21	2004	20	1981	31	27
1983	22	2008	20	1982	4	32
1999	23	1970	23	1983	22	9
2006	24	1978	24	1984	42	39
1978	25	2000	25	1985	10	28
2002	26	1971	26	1986	9	11
1979	27	1981	27	1987	37	34
1994	27	1985	28	1988	16	5
2007	29	1980	29	1989	7	5
1971	29	1979	30	1990	6	1
1981	31	1994	31	1991	40	37
1997	32	1982	32	1992	38	38
1993	33	1973	33	1993	33	35
1976	34	1987	34	1994	27	31
1964	35	1993	35	1995	8	16
1967	36	1969	36	1996	14	19
1987	37	1991	37	1997	32	13
1992	38	1992	38	1998	18	20
1973	39	1984	39	1999	23	14
1980	40	1968	40	2000	3	25
1991	40	1974	41	2001	14	1
1984	42	1972	42	2002	26	16
1968	43	1977	43	2003	11	10
1963	44			2004	16	20
1965	44			2005	5	7
1977	46			2006	24	14
1969	47			2007	29	8
1974	48			2008	12	20
1972	49			2009	1	4

Note: The rankings are ordered by vintage in the last two columns for reds and whites, respectively.

calculated for the bloom and ripening periods. Wind speed and pressure are each averaged to produce both a yearly value and a value for each phenological period.

Statistical methods

All comparisons are made between the top 10 and bottom 10 consensus ranked vintages for both red and sweet white wines (Table 1). First, a Mann–Whitney *U*-test is used to compare each climate variable for the high- and low-ranked vintages. The Mann–Whitney *U* is a non-parametric version of the *t*-test that does not require the data to be normally distributed (as is the case with some of our variables). The test statistic (*U*) is calculated based on a comparison of the magnitudes of the ranked variables in the two groups. This is run as a two-tailed test with a Type I error rate of 0.05 used to determine statistical significance.

Because many of the climate variables are highly correlated (e.g. maximum and minimum temperature, total precipitation, and number days with precipitation), principal components analysis (PCA) is used to identify those collinear variables and to remove all inter-variable correlation. Each principal component (PC) contains some portion of each variable – the PCs are ordered by the amount of the total explained variance with the constraint that each PC is orthogonal to all other PCs. This analysis is run using the correlation matrix of all variables as input. An unpaired, two-tailed *t*-test is calculated on the PC scores to determine if the mean PCs differ significantly ($\alpha \leq 0.05$) between the top 10 and bottom 10 ranked vintages.

Finally, discriminant function analysis (DFA) is used to determine the key climatic factors that distinguish between top- and bottom-ranked vintages. Separate DFAs are run on both the climate variables and their PCs in a stepwise manner. Similar to forward stepwise regression, this method first identifies the variable that best distinguishes between high- and low-ranked vintages and then determines if subsequent variables add significantly more discriminating power. The procedure is terminated when a convergence criterion is met.

Results/discussion

The consensus rankings for Bordeaux vintages show that 1961 and 2009 are tied for the best red wine vintages, followed by 2000, 1982, and 2005 (Table 1). The lowest ranked red wine vintages include mostly years from the mid-1960s through the mid-1970s, with 1972 given the lowest ranking of the 49 years. For sweet white wines, the top-ranked vintage was a tie between 1967, 1990, and 2001, while the mid-1970s have the lowest ranked vintages with 1977 the lowest of the 43 vintages. In the top 10 ranked vintages for both reds and whites, only four vintages appear in both rankings: 1989, 1990, 2005, and 2009. For the lowest ranked vintages, there is slightly more agreement, with seven common years in the bottom 10.

For red wines, the variables that differed significantly between the top 10 and bottom 10 ranked vintages were average, maximum, and minimum growing season temperatures, the average and maximum temperature and average DTR over the ripening period, precipitation during veraison and throughout the growing season, HI, GDD, and the average SP over the dormancy, bloom, and veraison time periods (Table 2). For sweet white wines, the key variables were average temperature, maximum, and minimum temperature, and precipitation over the growing season, the average and minimum temperature during the preceding dormant season, HI and GDD, the amount of sunlight during the bud break period, the number of precipitation days (P_{days}) during the bloom period, the average pressure over the ripening period, and the amount of precipitation in the veraison and ripening periods (Table 2). These results demonstrate that numerous climate variables contribute to wine quality at different phenological stages, with the

Table 2. Summary of the statistically significant relationships between consensus rankings for red and sweet white wines and climate variables during different phenological stages of the grapevine.

Wine type	Dormancy (1 Nov–31 Mar)	Bud Break (15 Mar–15 Apr)	Bloom (25 May–20 Jun)	Veraison (5 Aug–5 Sep)	Ripening (1–30 Sep)	Growing Season (1 Apr–31 Oct)	HI (1 Apr–30 Sep)
Red	SP↑		SP↑	P↓ SP↑	T↑ T_{max}↑ DTR↑	T↑ T_{max}↑ T_{min}↑ GDD↑ P↓	↑
White	T↑ T_{min}↑	Sun↑	P_{days}↓	P↓	P↓ SP↑	T↑ T_{max}↑ T_{min}↑P↓ GDD↑	↑

Notes: T, average temperature; T_{max}, maximum temperature; T_{min}, minimum temperature; P, precipitation; P_{days}, number of days with precipitation; and Sun, hours of direct sunlight. An upward-pointing (downward-pointing) arrow indicates a statistically significant direct (indirect) relationship between that climate variable and high rankings. For example, a high DTR during ripening is associated with higher ranked (better quality) red wines, whereas low precipitation during ripening is associated with good sweet white wine vintages. HI (last column) is shown independently because it was calculated over a slightly different time period.

best vintages associated with higher temperatures, large temperature diurnality, large heat accumulations (HI and GDD), low precipitation, and both high pressure and insolation.

The climatic conditions important to the production of high-quality red wines are somewhat different than those for sweet white wines (Table 2 and Table 3). For example, the amount of sunlight during the bud break stage is a significant factor for sweet white wines but not for red wines. Whereas SP during the dormant, bloom, and veraison periods is significant for red wine, it is important during the ripening period for sweet white wine. This relationship could indicate

Table 3. Mean values of climate variables found to be significantly different between the top 10 and bottom 10 ranked vintages for both red and sweet white wines.

		White		Red	
Time period	Variable	Top 10	Bottom 10	Top 10	Bottom 10
Dormancy (1 Nov–31 Mar)	T (°C)	8.1	7.2	**8.6**	**7.6**
	T_{min} (°C)	4.0	3.3	**4.7**	**3.6**
	SP (hPa)	**1020.2**	**1017.0**	1019.7	1018.6
Bud Break (15 Mar–15 Apr)	Sun (h)	137.1	119.4	**156.9**	**119.5**
Bloom (25 May–20 Jun)	P_{days}	10.6	13.3	**9.3**	**14.1**
	SP (hPa)	**1018.0**	**1016.2**	1017.6	1016.1
Veraison (5 Aug–5 Sep)	P (mm)	**28.1**	**88.6**	**44.4**	**99.5**
	SP (hPa)	**1018.7**	**1017.2**	1017.7	1017.1
Ripening (1–30 Sep)	T (°C)	**18.9**	**17.0**	18.3	20.5
	T_{max} (°C)	**24.8**	**22.2**	24.0	22.6
	DTR (°C)	**11.9**	**10.3**	11.4	10.5
	P (mm)	62.9	106.0	**47.6**	**115.1**
	SP (hPa)	1018.3	1017.1	**1018.9**	**1016.9**
Growing Season (1 Apr–31 Oct)	T_{max} (°C)	**23.2**	**21.2**	**23.3**	**21.6**
	T_{min} (°C)	**12.3**	**10.8**	**12.6**	**11.2**
	T (°C)	**17.8**	**16.0**	**17.9**	**16.4**
	P (mm)	**439.2**	**527.3**	**414.8**	**590.1**
	GDD (°C)	**1678.2**	**1304.9**	**1716.7**	**1391.8**
(1 Apr–30 Sep)	HI (°C)	**2106.7**	**1730.7**	**2131.2**	**1834.2**

Note: Bold variables are statistically significant ($\alpha = 0.05$) for that variable/wine combination.

that higher than normal pressure during ripening contributes to inversions and localized fog in the Sauternes and Barsac regions, which would aid in the development of noble rot. As expected, higher HI values are found primarily in the best vintages. Eight of the top 10 vintages, for both red and white wines, had HI values above 2000, while only 1 of the bottom 10 red vintages and 3 of the bottom 10 white vintages exceeded this HI value.

All of the top sweet white wine vintages experienced average growing season temperatures above 17.3°C, which is considered the optimum temperature over that time period (Jones et al., 2005b). However, the top red wine vintages showed somewhat more variability, with the average growing season temperatures ranging from 16.4°C to 18.8°C. The maximum and minimum temperatures for the growing season are highly related to the average temperature for the growing season, and the average temperature over each phenological period is also correlated with the average growing season temperature. However, for red wines, the ripening period temperature is key, with eight out of 10 vintages having an average temperature above 18.3°C. For sweet white wines, the dormant season temperature is also important, as 9 out of the top 10 vintages (but only 5 of the bottom 10) had an average temperature above 7.5°C. This dormancy relationship is inconsistent with some prior research showing a linkage between wet (rather than warm) dormant periods and higher wine quality (Ashenfelter, 2008; Jones & Davis, 2000; Jones & Storchmann, 2001). DTR during the maturation period is important for grapes to reach their potential (Gladstones, 1992), and for red wine the DTR during the ripening period is indeed significant – 9 of 10 top vintages had a mean DTR greater than 11°C.

Additionally, warm and dry conditions over the growing season – especially during the ripening period – provide the optimal conditions for the development of a balance between sugar accumulation and acid loss (e.g. Jones & Storchmann, 2001). Precipitation during the ripening period is ideally low with an average precipitation of 63 mm in the top 10 years for red wine and 48 mm for white wine – significantly less than the average of the bottom 10 vintages (106 and 115 mm for red and white, respectively).

Over the growing season, 7 of the top 10 ranked red wine vintages and 9 of top 10 ranked sweet white wine vintages had precipitation amounts less than 469 mm. Veraison precipitation is also significant in wine quality, with 9 of top 10 red wine vintages having less than 40 mm of precipitation and the top 2 having only 9 mm and 21 mm, respectively, in agreement with prior research (e.g. Ashenfelter, 2008; Jones & Davis, 2000; Jones & Storchmann, 2001; van Leeuwen et al., 2009). Sweet white wine vintages had similar results, with 8 of the top 10 vintages receiving less than 52 mm of precipitation over the veraison period. Poor sweet white wine vintages also typically had about five more days with measurable precipitation in the bloom period than did the top vintages. Over the course of the growing season, highly ranked vintages received less rainfall than lower ranked vintages, but the differences became increasingly important as the grapes matured (Figure 1). Veraison seems to be particularly important for red varieties as the mean veraison rainfall during top 10 vintages is only one-third of what is received during bottom 10 years.

It is instructive to summarize the climate differences between the extremes of the rating distribution – to compare the climate of the top- and bottom-ranked vintages. For Bordeaux red wines, the top vintage was a tie between 1961 and 2009; the lowest ranked vintage was 1972. Not surprisingly, in the top-ranked years, the mean growing season temperature was 3°C higher than in 1972. The temperature difference was particularly evident during the ripening period. Likewise, HI was 40% higher, GDD was 50% higher, and the growing season saw 50% (almost 400) more sunshine hours. The precipitation differences are less intuitive. The top-ranked vintages saw almost twice as much precipitation and twice as many precipitation days during the ripening period, but only one-tenth the precipitation during veraison. Over the entire growing season, total rainfall between these extreme vintages is almost identical – the

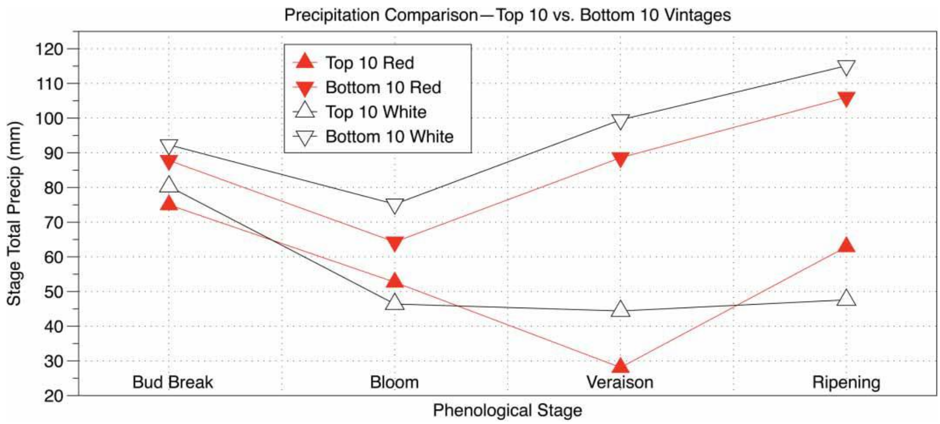

Figure 1. Comparison of mean precipitation by phenological stage for the top 10 and bottom 10 ranked vintages for both red and sweet white wines.

critical factor is the timing of the rain. Bordeaux sweet white wines exhibited similar temperature patterns to the reds. The top vintages (1967, 1990, and 2001) were 2°C warmer over the growing season than the bottom vintage (1977) and both HI and GDD were about 30% higher. But in contrast to the reds, where precipitation was similar between the top and bottom vintages, the top sweet white wine vintages were 20–50% drier throughout most of the growing season than the lowest ranked vintage.

In the PCA, the first three components cumulatively accounted for 58% of the total variance in the entire set of independent variables. This indicates the presence of a fairly high degree of intercorrelation (or lack of independence) between the climatological parameters. The key variables included in each of the three key components along with the sign of their relationship to each PC are shown in Table 4.

The first PC contrasts years characterized by warm, sunny, calm growing seasons with high heat accumulations to cool, windy years. The second PC emphasizes weather conditions during the ripening period, contrasting warm years with clear skies (and thus a large DTR), and lack of precipitation to years in which ripening was dominated by more rainfall and cooler, cloudier conditions. The third PC is difficult to assess and includes a variety of variables during different phenological stages of the grapevine. A *t*-test comparing the PC scores for high- vs. low-ranked vintages indicates that the first three PCs were significantly different at the alpha 0.05 level for red wines and only the first two PCs differed for sweet white wines.

Stepwise DFA is run in an attempt to identify those key variables that best distinguish between good and poor Bordeaux vintages. This is done for both the original (raw) variables and the PCs.

For red wines, T_{max} during the growing season is a key discriminator. When T_{max} is combined with either SP during bloom or P during dormancy, the two-variable discriminant model correctly places 19 of 20 vintages (in the top or bottom ten). With the addition of a third variable, total precipitation during the growing season, perfect prediction is achieved.

The SP (bloom) vs. T_{max} relationship is shown in Figure 2 (top). The unstandardized discriminant equation is

$$0.277\text{SP(bloom)} + 1.274T_{max}(\text{growing season}) - 259.107 = 0. \tag{4}$$

The top 10 vintages are obviously much warmer than the bottom 10 and experience higher pressure during the bloom period in most years; 9 of the top 10 vintages have mean growing

Table 4. Summary of variables with high (positive and negative) loadings for the first three PCs and the variance accounted for by each.

	Positive	Negative
PC 1 (33.8%)	T, growing season	WS, growing season
	T_{min} growing season	WS, bloom
	GDD	WS, veraison
	Sun, growing season average	WS, ripening
	Sun, growing season total	
	Sun, bloom	
	Sun, veraison	
	Sun, ripening	
PC 2 (13.7%)	T, ripening	P, ripening
	$T_{max,}$ ripening	P_{days}, ripening
	DTR, ripening	P, growing season
	SP, ripening	
PC 3 (10.0%)	T_{min}, ripening	SP, ripening
	HI	
	T_{max}, dormancy	
	DTR, dormancy	
	WS, bud break	
	WS, dormancy	
	SP, dormancy	

Note: WS, wind speed; other variables are as defined in Table 2.

season maximum temperatures greater than 22°C. The misclassified vintage, 1991, was unusually warm for a bottom 10 vintage. The high heat accumulations and thus large values of HI and GDD make 1991 more consistent with a top 10 vintage. However, this year experienced the highest growing season precipitation of any year in the bottom 10. Additionally, a heavy frost event in April destroyed the vegetation, and despite the formation of new buds by late May, the vine phenology was too delayed to produce a high-quality vintage despite the generally favourable climatic conditions for the remainder of the growing season.

An equally good discrimination was found using precipitation during the dormant period (Figure 2(b)). The equation in this case is

$$0.007\mathrm{P(dormant)} + 1.756T_{max}(\text{growing season}) - 41.856 = 0. \tag{5}$$

The two years with the highest maximum temperatures during the growing season were preceded by low dormancy precipitation. Otherwise, there is little difference in dormant precipitation between top 10 and bottom 10 vintages. For this reason, the growing season T_{max} model (Figure 2 (a)) is more intuitive from a viticultural standpoint.

For sweet white wines, the key discriminating variables between top 10 and bottom 10 vintages are growing season precipitation and maximum temperature and minimum temperature during the dormant period. Any two-variable combination of these three resulted in a correct classification of 19 out of 20 vintages.

The simple combination of growing season maximum temperature and precipitation results in a very strong discrimination between most vintages (Figure 3(a)). The unstandardized equation is

$$1.032T_{max}(\text{growing season}) - 0.007P(\text{growing season}) - 19.855 = 0. \tag{6}$$

Most top 10 sweet white wine vintages were warm and dry and many bottom 10 vintages were cool and/or wet. There is some overlap between moderately warm and moderately wet vintages in

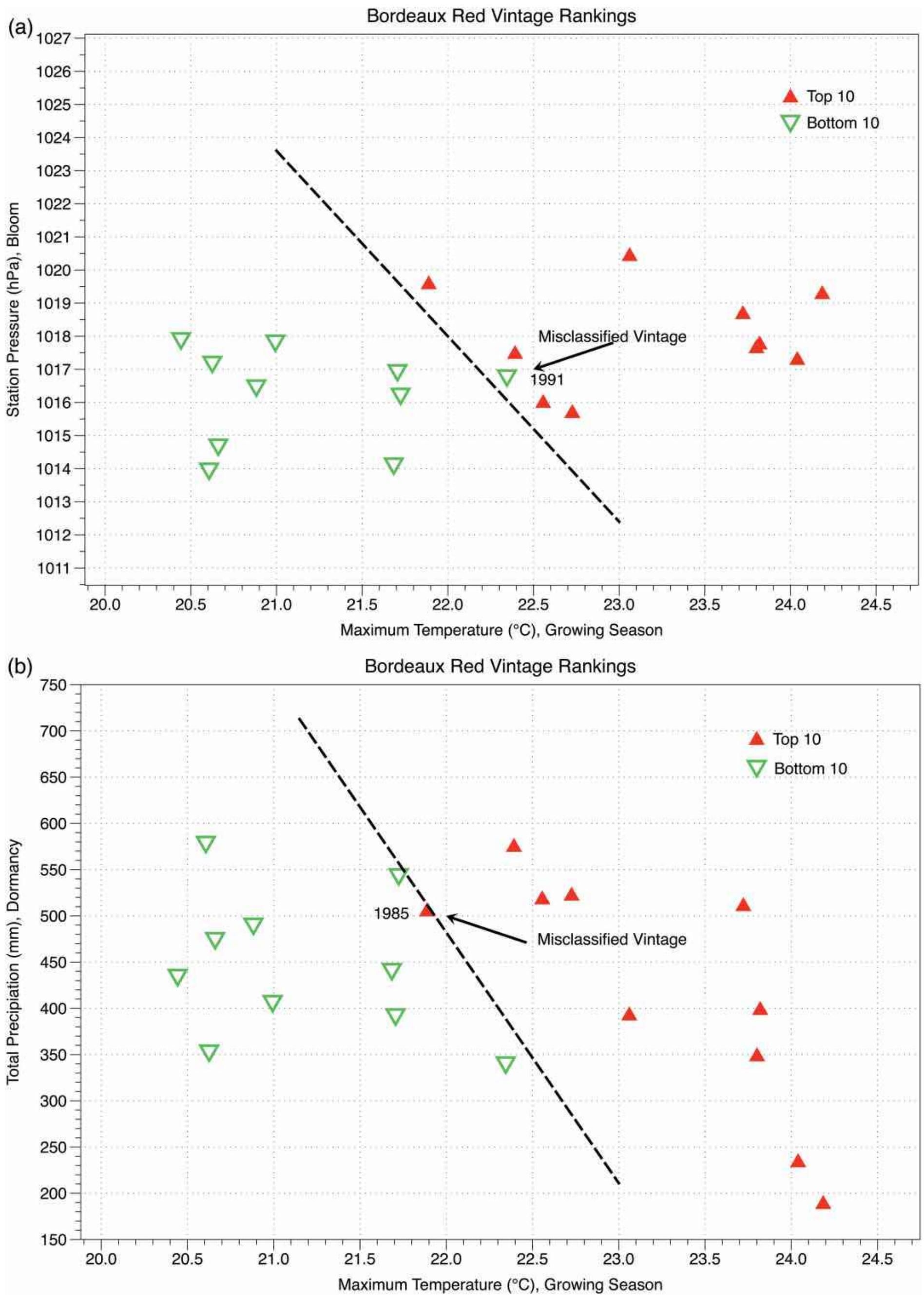

Figure 2. The best discriminators between top 10 (filled, red triangles) and bottom 10 (open, green triangles) red vintages in Bordeaux are maximum temperature during the growing season coupled with either SP during bloom (a) or precipitation during the dormant period (b). The discriminant function is indicated by the dashed line. The lone misclassified vintage is identified for each case.

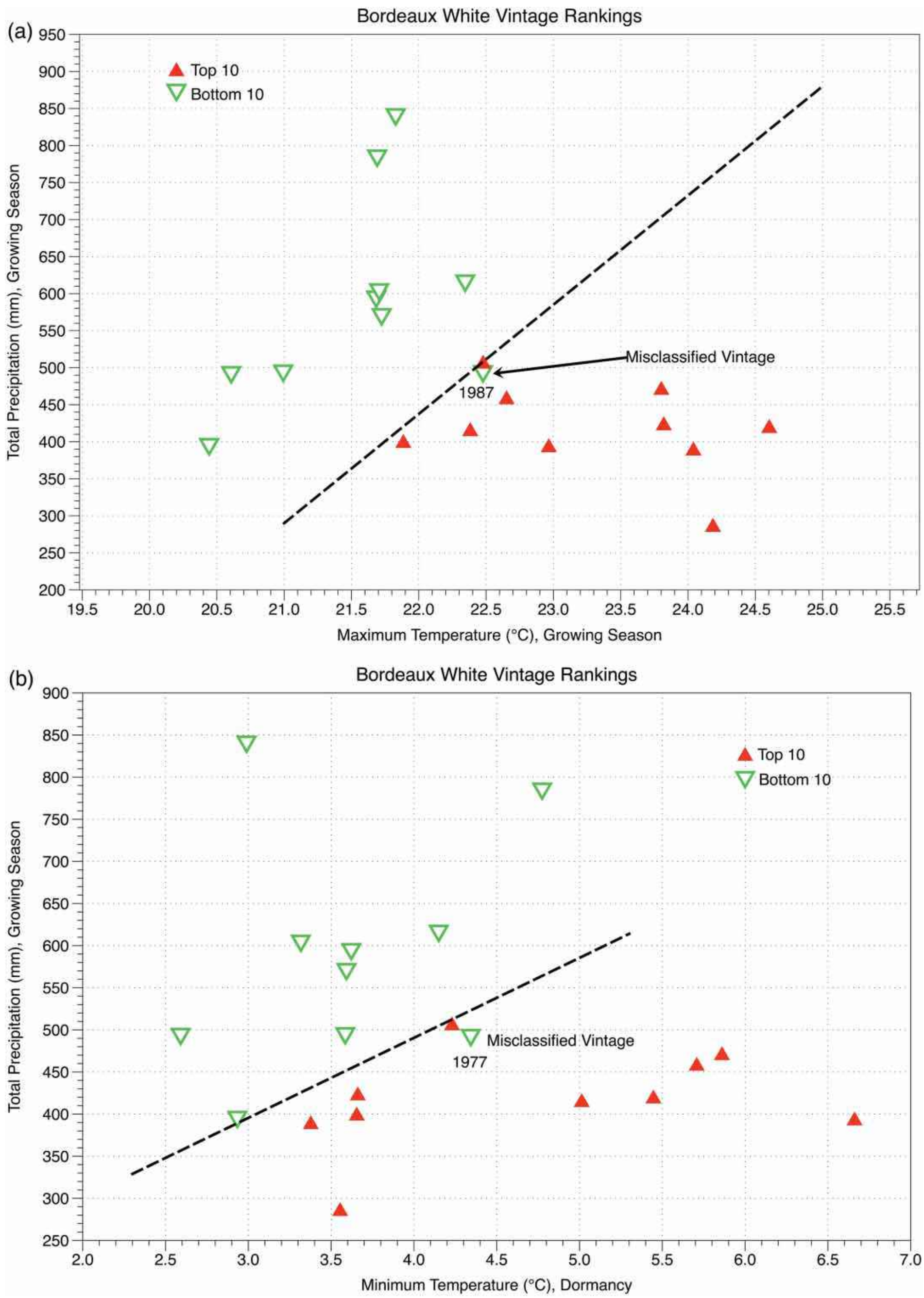

Figure 3. Same as in Figure 2, but for Bordeaux sweet white wines: growing season maximum temperature and precipitation (a), growing season precipitation and dormancy minimum temperature (b), and growing season maximum temperature and dormancy minimum temperature (c). In each case, 19 of 20 vintages were correctly classified.

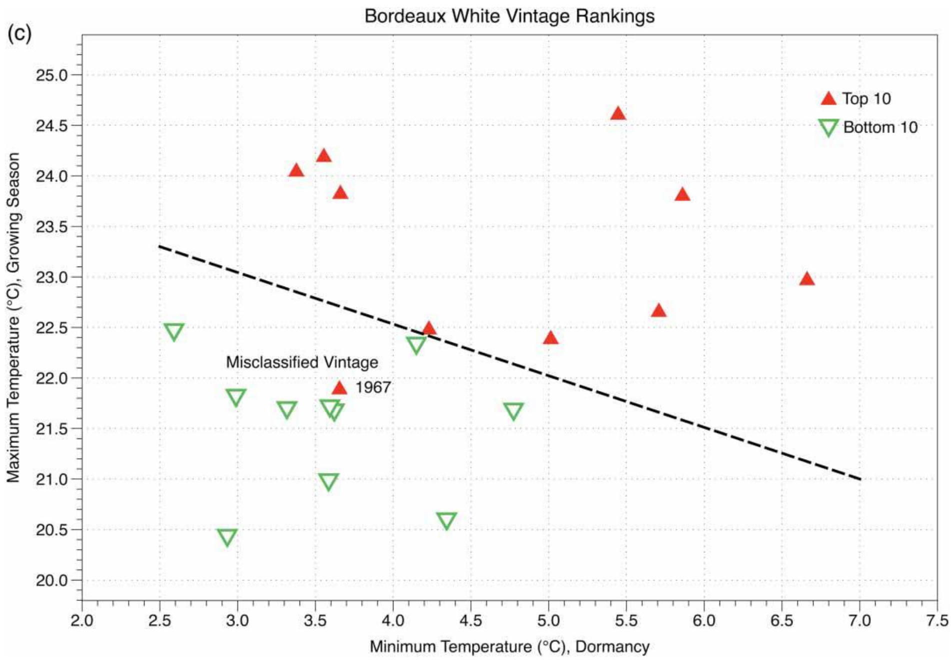

Figure 3. Continued.

the two groups. Of the top vintages, only 1983 has total precipitation greater than 500 mm (505 mm), which was a mere 10 mm greater than 1987, the misclassified vintage that had essentially the same maximum temperature as 1983. Thus, with slightly cooler or wetter conditions in 1987, this two-variable pair would produce a perfect discrimination.

Results using growing season precipitation and minimum temperature during dormancy are quite similar (Figure 3(b)). The equation for this case is

$$0.008\text{P(growing season)} - T_{\text{min}}\text{(dormant)} - 1.105. \tag{7}$$

Warm nights during the dormant period were a good predictor of vintage quality in five of the top 10 years. The other five years, which were cooler, tended to have fairly dry growing seasons. Nine of the bottom 10 sweet white vintages had some combination of a cold dormant and/or a wet growing season. The lone misclassified year, 1977, was actually warmer (during dormancy) than five of the top 10 vintages but only drier than one year. In many respects, 1977 had a lot of other characteristics of a poor vintage: heat accumulations were low (along with sunshine hours), the bloom period was wet, and most of the phenological stages were characterized by low pressure and high winds – conditions indicative of numerous storm events. So in this case, the moderately high dormant season minimum temperatures were not predictive of subsequent vintage quality.

Finally, examination of the growing season maximum temperature vs. dormancy minimum temperature provides some unexpected results (Figure 3(c)). The unstandardized discriminant function is

$$1.105T_{\text{max}}\text{ (growing season)} + 0.564T_{\text{min}}\text{(growing season)} - 27.105 = 0. \tag{8}$$

It is noteworthy that the bottom 10 sweet white vintages cluster in the bottom left of the figure – they had cool growing seasons that were preceded by a cool dormant period. However, it is clear that a cool dormancy is not predictive, given that 5 of the top 10 sweet white wine vintages subsequently saw warm to hot growing seasons.

The 1967 vintage is a very interesting misclassification, given that it was tied for the highest consensus ranking for sweet white wines. GDD were almost 200 units lower than the next lowest top 10 vintage, so other climatic factors were sufficient to overcome this low heat accumulation. Dormancy was characterized by very cool nights, calm conditions with low pressure, and relatively low precipitation (an unusual climatic combination). Overall, 1967 was the 10th driest year (out of 43) with just under 400 mm of precipitation. It is not obvious from a climatic standpoint why 1967 garnered such a high rating, however localized conditions leading up to harvest may have contributed to ideal noble rot development in Sauternes and Barsac.

For both red and white wines, we performed discriminant analyses using the PCs instead of the raw variables. In no case did the PC-based discrimination provide superior results to the raw variable runs. Given the inherent difficulty associated with interpreting some of the PCs, we did not continue to evaluate the PC-based results.

For years when both red and sweet vintages were rated (1967–2009), we compared the consensus rankings. In general, the rankings are highly correlated (Spearman's $\rho = 0.66$, $p < 0.001$), so good vintages for red wines also tend to be good vintages for sweet whites. However, many years exhibit very large differences. Figure 4 shows the red and sweet white consensus rankings for each vintage (recall that low numbers represent better quality wines). Most of the points fall close to the 1:1 line, suggesting overall consistency. This is particularly true for the lower ranked vintages (upper right portion of Figure 4), which suggests that when the overall vintage climate is not favourable, both red and sweet white wines tend to be of lower quality. However, note the large spread of ratings towards the bottom left of the figure, which indicates large differences

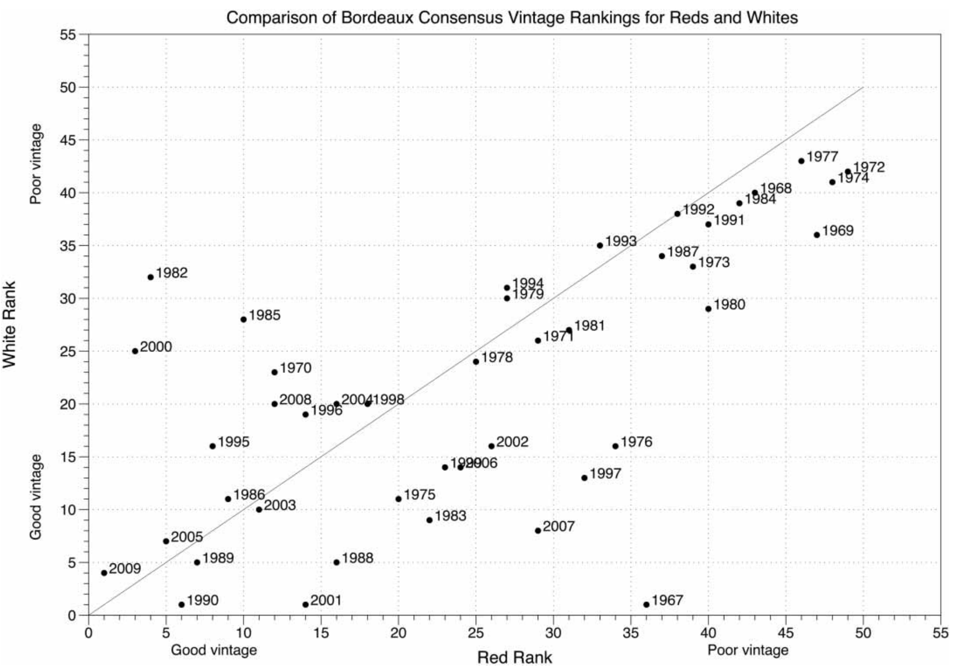

Figure 4. Rankings, by year, of sweet white vs. red wines, with lower quality vintages towards the top right. A 1:1 line is included for reference. Years with markedly different rankings between sweet whites and reds are found farther from the 1:1 line.

between red and sweet white wine quality in some years. For example, 1967 was (tied for) the top-ranked year for sweet white wines, but reds were only ranked 36th out of 49; 1982, 1985, and 2000 were top 10 years for red wines but only in the bottom half for sweet whites. Is there a climatic component that can distinguish between years that favour the growth of red vs. white grape varieties and therefore wine quality?

We again perform DFA to compare red and sweet white vintages. First, because the differing lengths of the two data-sets could impact the rankings, the rankings are standardized within red and sweet white wines on a 100-point scale. Second, the differences between these standardized rankings between reds and sweet white wines are calculated for each year. Third, the differences are sorted, and the top and bottom 10 ranked vintages are flagged (as in the previous analysis). Finally, stepwise discriminant analysis is run on these differences to determine if years in which red wines markedly outperformed sweet white wines could be distinguished climatically from years in which sweet white wines were superior.

Three climate variables proved to be critical in the discrimination: precipitation and SP during bloom and DTR over the entire growing season. Rainfall during the bloom stage alone correctly classified 75% of the vintages; the three-variable combination produced a correct classification in 18 of 20 cases. Figure 5 demonstrates the relationship between the two critical bloom stage variables – total precipitation and surface pressure. Higher pressure would tend to be associated with lower precipitation amounts, which together would tend to indicate conditions conducive to more complete flowering. These results show that white grapes tended to perform better in drier, higher pressure bloom stages, whereas red grapes appear to excel across a higher range of bloom stage

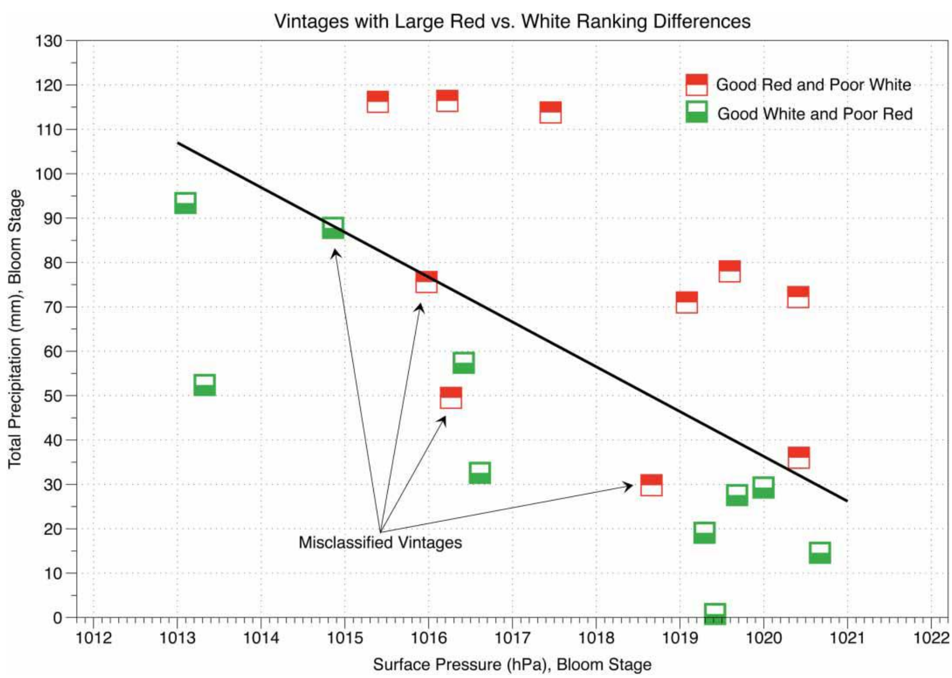

Figure 5. The climatic factors that best discriminate between the years when red and sweet white ranks differed most are precipitation and SP during the bloom phenological stage. These two variables correctly classified 16 of the 20 vintages as being good red/poor white (red symbol, filled top) vs. good white, poor red (green symbol, filled bottom).

precipitation levels. On average, years in which reds outperformed whites received 75.9 mm of bloom precipitation whereas vintages in which whites excelled saw only 41.5 mm.

Conclusions

Given that winegrapes are native to Mediterranean climates characterized by hot, dry summers, it is not surprising that top-ranked Bordeaux vintages are associated with high heat accumulation over the growing season, high insolation levels, high pressure, and a general lack of precipitation. By examining climate differences bounded by typical grapevine phenological stages, the importance of weather conditions during the final pre-harvest veraison and ripening period is highlighted. Specifically, the top 10 ranked red wine vintages are characterized by higher than normal pressure, a lack of rainfall, and days with large DTRs during these key pre-harvest periods. As long as the year receives adequate heat accumulation, other weather factors earlier in the season do not appear to be critical in determining ultimate vintage quality. Although sweet white wines also exhibited a preference for low rainfall and high heat accumulation, early season climatic factors differ between high- and low-quality vintages. Specifically, highly ranked sweet white wine vintages have relatively high temperatures during dormancy, plentiful sunlight in the bud break period, and comparatively few rain days during the bloom period.

Although 13 climate variables differed significantly between the top 10 and bottom 10 ranked vintages for both red and sweet white wines, many of these variables are inter-correlated. Through the use of DFA, we determined that high maximum temperature during the growing season was the main factor in determining top 10 over bottom 10 vintages for red wines. Additional discriminating variables were precipitation during the dormant period and SP during the bloom stage. Coupling $T_{\max}$ with either of these variables correctly classified 19 of the 20 vintages examined. For sweet white wines, growing season precipitation and maximum temperature and dormancy minimum temperature were the most critical factors. Any combination of two of these three variables resulted in 95% correct classification of the vintage.

We additionally examined if climatic factors could help explain those unusual years in which red wines were ranked much higher than white wines (or vice versa). Again using DFA, we found that bloom stage precipitation was the most important factor, with generally wetter conditions in years when reds were ranked much higher than whites. One possible explanation for this result, and a study limitation, is the lack of variety-specific phenological information for each vintage. Because we employed average phenological dates to classify each stage (Jones & Davis, 2000; Jones et al., 2005a), the varied flowering dates of the red and white varieties grown in Bordeaux could result in some grapes just starting bloom while others are finished and in the berry set stage. Thus, in the absence of additional phenological data, these results could be reflecting either a bloom stage difference in precipitation timing or the greater sensitivity of white grapes to bloom stage rain events. Another possible source of error is our use of precipitation rather than a water balance approach to gauge growing conditions. Future research might benefit from the use of a soil dryness index (based on data availability) to characterize soil moisture status throughout the growing season.

When one uses the price to determine the quality of a certain vintage, the market at the time of sale, the effect of growers trying to maintain their income, and the age at which the bottle is sold are all factors in determining the price paid (Ashenfelter, 2008). By using a consensus ranking, we attempted to minimize these factors as well as the specific biases of individual reviewers (Borges et al., 2012). An implicit assumption in our approach is that vintage ratings are consistent over time even though different individuals are typically involved in making those ratings. Thus, a red vintage rated 95 in 1950 should be comparable to a red vintage rated 95 in 2001. Although these ratings are clearly subjective, we believe that the consensus approach provides a level of stability in the assessment of vintage quality.

As the global climate changes, locations that currently produce outstanding wine may lose that advantage to other regions (Butterfield, Gawith, Harrison, Lonsdale, & Orr, 2000; Jones et al., 2005b; Kenny & Harrison, 1992). It would be interesting to examine the threshold values of key climatic variables identified in this study in the context of climate change to examine potential changes in the likelihood or frequency of high-quality vintages in the future.

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