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The effect of climate on Burgundy vintage quality rankings

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ABSTRACT

Aim: Based on consensus rankings from prominent rating authorities, we examined the importance of a suite of climatic variables, organized by winegrape phenological stage, in distinguishing between high- and low-ranked vintages in Burgundy.
Methods and Results: Vintage ratings of Burgundy wines acquired from 12 sources were evaluated to develop consensus rankings for red and white wines from 1961–2015. Climate variables (air temperature, precipitation, degree-day accumulations, etc.) were organized by mean phenological stage and compared between good and poor vintages using Mann-Whitney U tests and multivariate stepwise discriminant function analysis. High temperatures, particularly during the growing season, were found to be the most consistently important climatic factor in distinguishing good-quality vintages from poor-quality vintages. The best red vintages had a greater diurnal temperature range during the growing season, whereas the top white vintages were not distinguished by unusually warm conditions, but the bottom-ranked white vintages were particularly cool and wet. The impact of rainfall varied across the growing season, with top-ranked Burgundy wines benefitting from rainfall during the bud break period and dry conditions during the ripening phase.
Conclusions: The most important climatic factor in distinguishing between top- and bottom-ranked vintages is growing season temperature, especially high diurnal temperature range (for reds) and high average maximum temperatures (for whites). Good Burgundy vintages are more likely when there is ample rainfall during the bud break period in April and dry conditions during the véraison and ripening phases.
Significance and Impact of the Study: As viticulturalists adapt to regional climate trends, a better understanding of how specific climate variables affect wine quality becomes increasingly important in viticulture management.

KEYWORDS

Burgundy, climate, vintage quality, vintage rating, consensus ranking

INTRODUCTION

Although there is general knowledge of the weather and climate conditions associated with good vintages and high-quality wines—adequate precipitation and warmth to grow the vine and ripen the fruit, with few if any weather extremes (like frost, hail, and heat waves) or the conditions that lead to disease—comprehensive analyses of the overall effects are limited (Jones, 2014). Part of the challenge is that quantifying wine quality is difficult given the lack of one universal and widely-accepted quality measure that allows for objective assessments. The problems are that no one chemical measure will ever be more than partially successful, and that wine quality is primarily subjective and strongly influenced by extrinsic factors (Jackson, 2017). Even if we could solve the wine quality question, most weather and climate studies use a few metrics that are often averaged or summed over the entire dormant period or growing season and may not capture the most important influences (Ashenfelter *et al.*, 1995).

The most often used wine quality metrics are price and vintage ratings. Wine prices, either at release or at auction, have been used by many to assess aspects of quality and economics (Ashenfelter *et al.*, 1995; Storchmann, 2012; Oczkowski & Doucouliagos, 2015; and others). In an analysis on Bordeaux wines, Ashenfelter (2010) shows that knowledge of the château (essentially the vineyard) and vintage weather provides most of the information needed to determine the quality of the wine. From this work, it would appear that price is an efficient predictor of quality; however, price also reflects age, rarity, and the reputation of the producer. As another surrogate for quality, vintage ratings are published by internationally recognized critics, magazines, or organizations, and compare and contrast wines from different properties, different regions, or different vintages. Ratings and prices have been linked. Jones & Storchmann (2001) found that wine market prices are sensitive to vintage ratings and Schamel & Anderson (2003) determined that regional reputations in New Zealand and Australia have a significant effect on the price premium paid by consumers.

Although numerous rating systems, compiled over various time periods and by various sources, exist, they commonly have varying numerical scales and criteria, and each publisher has its own tasting panel, with its own criteria and perception of quality, which tastes a different set of wines at different times and under different conditions (Borges *et al.*, 2012). Even though correlations between the sources are generally moderate to strong ($0.4 < r < 0.9$), they can vary substantially between raters. To address these issues, Borges *et al.* (2012) developed a consensus ranking method that converts ratings of individual sources using a rank aggregation algorithm. The ranking produces an objective consensus of the collection of input vintage charts that is a robust metric of overall vintage quality (Ashenfelter *et al.*, 1995; Ashenfelter, 2010).

Research examining weather and climate relationships on vintage ratings or price has found that they accurately reflect the factors long known to determine wine quality. For example, Ashenfelter (2010) determined that winter rainfall, growing season temperatures, and harvest rainfall combined to explain more of the variation in price than in ratings in Bordeaux. Jones & Storchmann (2001) found that warm, dry summers lead to higher ratings and prices, although some varieties/regions are more sensitive than others. In four regions in Australia, Soar *et al.* (2008) found that maximum temperatures prior to harvest were important at differentiating top- and bottom-rated vintages and that the effect varied between cool and warmer regions. Examining a consensus ranking of vintage ratings (Borges *et al.*, 2012) for Bordeaux, Baciocco *et al.* (2014) concluded that good vintages had higher heat accumulation during the growing season and a general lack of rainfall nearing the ripening stage compared to poor vintages. In addition, using a long-term vintage series from wine brokers Tastet & Lawton, van Leeuwen *et al.* (2009) observed that red Bordeaux ratings were never low in years with elevated water deficit-related stress from the véraison stage to harvest. In Tuscany, Salinger *et al.* (2015) found similar results, with higher heat accumulation during the growing season and low rainfall during the ripening stage as the main discriminators between good and poor vintages. Their research also tied large-scale weather types over Europe to the local weather and climate characteristics that influence wine quality in the region. Real *et al.* (2017) conducted a climatology on consensus rankings of ratings on Vintage Port wine from the Douro Valley of Portugal and found that higher than average winter and growing season temperatures and lower heat stress during the ripening period differentiated good and poor vintages. Jones *et al.* (2005) also concluded that growing season average temperatures have a marginal effect of a 13-point increase in vintage ratings during a growing season that is 1.0°C warmer than average.

To add to our knowledge of climate influences on vintage quality, this research examines Burgundy, one of the world's most historic and renowned wine regions. Since the late Middle Ages, the region has largely been regarded as one of the highest quality wine producing regions in the world (White *et al.*, 2009). As of 2017, Burgundy was the 8th largest wine region in France in terms of acreage (3.7% of France's vineyards) and production (6% of all French AOC wines (BIVB, 2017)). The region produces 61% white wines, 28% red or rose wines, and 11% Crémant de Bourgogne (sparkling) and includes Chardonnay (~50%), Pinot Noir (41%), Aligoté (6%), and Gamay Noir (2.5%) varieties. Nearly half of Burgundy wines are exported, primarily to the United States and the United Kingdom.

The goal of this paper is to identify those climatic factors that best determine the quality, as defined by a consensus ranking, of Burgundy vintages for both red and white wines. We apply this consensus ranking approach, previously used in Bordeaux (Baciocco *et al.*, 2014), Tuscany (Salinger *et al.*, 2015), and Portugal (Real *et al.*, 2017), to Burgundy wines.

MATERIALS AND METHODS

1. Rating scales and vintages

Red and white Burgundy vintage quality ratings from 12 authoritative wine sources were obtained covering the period 1961–2015 (Table 1). Although the scales and criteria vary between raters and rating sources, by using an objective within-rater ranking method, it is possible to produce a consensus ranking.

TABLE 1. Rating scales and vintages used in the study by rating source for red and white Burgundy wines.

Rating Agency	Rating Scale	Red Wines	White Wines
Andy Bassin	0–100	1978, 1980–2013	1978, 1980–2013
BB&R	0–10	1978–2015	1978–2015
Broadbent	0–5	1961–62, 1964–67, 1969–2005	1961–62, 1964, 1966–67, 1969–71, 1973, 1976, 1978–79, 1982–83, 1985–86, 1988–2005
Clive Coates	0–20	1961–62, 1964, 1966–67, 1969–71, 1976, 1978–80, 1982–83, 1985–2005	1961–62, 1964, 1966–67, 1969–71, 1976, 1978–80, 1982–83, 1985–2005
Decanter	0–5	1961–70, 1972–2015	1961–89, 1991–2015
DeLong	0–5	1987–2014	1987–2015
Alexis Lichine	0–20	1961–73	1961–73
Sotheby's	0–100	1976–2010	1969–2003
Vintages.com	0–10	1970–2015	1974–2015
Wine Advocate	0–100	1970–71, 1974–75, 1978–2015	1970–71, 1975–76, 1978–2015
Wine Enthusiast	0–100	1984–2015	1984–1990, 1992–2015
Wine Spectator	0–100	1969–2014	1980–2015

2. Consensus ranking's method

We used the method developed by Borges *et al.* (2012) to examine both red and white wines across the 12 rating sources. The method converts the ratings of each individual source into rankings and uses a rank aggregation algorithm to combine the input ranking into a consensus ranking over the 55 years. The method begins by ranking each year within each rating source. To then determine the mean ranking across all sources, all pairs of years are examined to determine the preference rank between those years (or the number of times a year A is preferred over year B across all rating sources). Kendall's tau statistic is used to determine the mean distance of a given rating source from the mean (or combined) rank. An iterative sorting algorithm is then used to determine the final, consensus ranking across all sources based on the tau statistic. In our research, a missing year for a single source is replaced by the mean of the other raters who provided scores for that vintage.

3. Weather data

Daily weather data were obtained from Météo-France for the Dijon weather station (5.088°E; 47.267°N) for 1961–2015. Variables recorded include minimum (T_{min}), maximum (T_{max}), and daily average (T_{avg}) air temperatures, where T_{avg} is simply the mean of T_{min} and T_{max}. Diurnal temperature range (DTR) is T_{max} minus T_{min}, and the number of days with temperatures at or below freezing (0°C, FD) and at or above 35°C (HD) are also recorded. Precipitation (P_{total}) is daily total rainfall (mm) and the number of days with measureable (≥ 0.1 mm) precipitation (P_{days}) is also tabulated. As a proxy for relative wetness or dryness, the difference between precipitation and evapotranspiration is computed (P−ET) where evapotranspiration is approximated using Hargreaves' method; as is customary, this variable is summed over the relevant period (Hargreaves & Samani, 1985). Furthermore, two additional derived variables based on growing season heat accumulation are calculated. Growing degree-days (GDD) is the number of degrees by which temperature exceeds a 10°C baseline, calculated using daily average temperature as accumulated during 1 April–31 October:

$$\mathrm{GDD} = \sum_{i=1}^{n} \max\left[\frac{(Tmax+Tmin)}{2} - 10^{\circ}\mathrm{C}, 0\right]$$

(equation 1)

where *n* is the number of days. On days when T_{avg} < 10°C, no GDDs are accumulated. A similar variable is the Huglin Index (HI), which gives more weight to maximum temperature:

$$\mathrm{HI} = \sum_{i=1}^{n} \max\left[\frac{(Tavg-10^{\circ}C)+(Tmax-10^{\circ}C)}{2}, 0\right] * d,$$

(equation 2)

where is a correction factor that accounts for daylight variability as a function of latitude (in this case for Burgundy, d = 1.05) (Huglin, 1978). HI is calculated from 1 April–30 September.

The climate data were organized by average phenological stage of grapevine growth observed for Pinot Noir at Domaine Louis Latour just south of Dijon (Bois, 2013). Dormancy (dor) is defined from 1 November of the previous year through 31 March for the year in question and the growing season (gro) is from 1 April through 31 October. The growing season is further separated into discrete periods defined as "bud break" (bud), from 5 April through 31 April, "bloom" (blo), from 1 June through 15 June, "véraison" (ver) from 1 August through 20 August, and "ripening" (rip) from 1 September through 30 September. Other than GDD and HI, which are summed over the season, each of the daily weather variables is either summed or averaged for each phenological stage for each year/vintage. A total of 56 individual weather/climate variables were considered in the analysis. Complete annual climate data are provided in Supplementary Table 1.

4. Statistical analysis

Rankings were obtained for the 55 vintages between 1961–2015 and climate variables were compared between the top 10 and bottom 10 ranked vintages during this period. Because some of the climate variables are not normally distributed, the non-parametric Mann-Whitney U test for significance was used to identify statistically significant mean differences between the two groups, based on a type I error rate of 0.05. In addition, multivariate discriminant function analysis (DFA) was used to determine those climate variables that best differentiate between top 10 and bottom 10 ranked vintages. DFAs were run in a stepwise manner by first identifying the best overall discriminator and then selecting the variable that optimally discriminates among the remaining vintages that are incorrectly classified after step one. This process is repeated until a convergence criterion is met. All analyses were completed separately for the red and white rankings.

RESULTS

The climate of the Burgundy region is a modified maritime to semi-continental climate with cold winters, warm summers, and precipitation year round (Joly *et al.*, 2010). During 1961–2015, annual precipitation in Dijon was 760 mm with the growing season of April through October accounting for 60% of the annual precipitation (453 mm) and ranging from a low of 250 mm in 1964 to a high of 684 mm in 2013. Although the winters average 4.2°C, temperatures drop below –10°C during many dormant periods and the lowest temperature observed during this period was –21.3°C during the winter of 1985. The average growing season temperature for the Dijon station was 15.6°C which classifies it as a cool climate maturity region for viticulture (Jones *et al.*, 2005). GDD is 1271 on average, a Winkler Region Ib (Anderson *et al.*, 2012), while HI is 1743°C on average or a cool climate classification (Huglin, 1978). Precipitation during the ripening phase averages 64 mm but has been as low as 9 mm during 2004 and as high as 265 mm in 1965. P–ET is always negative for the site, averaging –274 mm total during the growing season, and exhibiting a range from –532 mm in 2003 to –8 mm in 2013. The site experiences three freezing days per year on average during April through October, but has seen as many as nine during 2003. Spring frost events during the bud break period typically occur from 10–15 April, but have occurred as late as 27 April during a period of devastating frosts in 2017 (not in our period of record). Heat events over 35°C occur only once per year on average, but nine occurred in 2015 and the 2003 growing season experienced 15. DTR during the growing season and during the ripening stage averages 10.3°C.

The highest ranked years for Burgundy red and white wines, according to the consensus ranking, were 2005 and 2014, respectively (Table 2). The top 10 Burgundy red vintages were in the earliest decade examined, the 1960s, and between 1990 and 2015 (Figure 1). Similarly, the top 10 Burgundy white vintages are also limited to three years from the decade of the 1960s and from 1989 through 2014. Neither category of top-ranked vintages includes any years between 1970 and 1988. In the consensus rankings, 1977 was an especially poor year for Burgundy wines, as its position was the lowest ranked for white wines and runner-up for the worst of the red vintages, second only to 1975. Neither the bottom 10 rankings for the reds nor

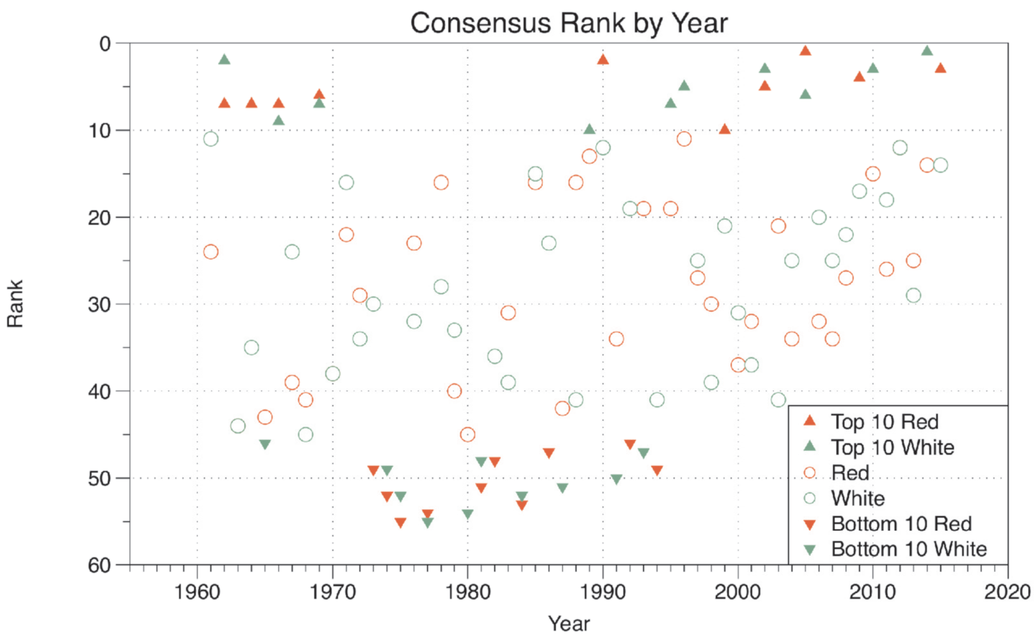

FIGURE 1. Consensus rank by vintage for Burgundy red and white wines.

TABLE 2. Vintage consensus rankings for Burgundy red and white wines.

Year	Red Rank	White Rank	Red Rank	Year	White Rank	Year
1961	24	11	1	**2005**	1	**2014**
1962	7	2	2	**1990**	2	**1962**
1963	44	44	3	**2015**	3	**2002**
1964	7	35	4	**2009**	3	**2010**
1965	43	46	5	**2002**	5	**1996**
1966	7	9	6	**1969**	6	**2005**
1967	39	24	7	**1962**	7	**1969**
1968	41	45	7	**1964**	7	**1995**
1969	6	7	7	**1966**	9	**1966**
1970	38	38	10	**1999**	10	**1989**
1971	22	16	11	**1996**	11	**1961**
1972	29	34	12	**2012**	12	**1990**
1973	49	30	13	**1989**	12	**2012**
1974	52	49	14	**2014**	14	**2015**
1975	55	52	15	**2010**	15	**1985**
1976	23	32	16	**1978**	16	**1971**
1977	54	55	16	**1985**	17	**2009**
1978	16	28	16	**1988**	18	**2011**
1979	40	33	19	**1993**	19	**1992**
1980	45	54	19	**1995**	20	**2006**
1981	51	48	21	**2003**	21	**1999**
1982	48	36	22	**1971**	22	**2008**
1983	31	39	23	**1976**	23	**1986**
1984	53	52	24	**1961**	24	**1967**
1985	16	15	25	**2013**	25	**1997**
1986	47	23	26	**2011**	25	**2004**
1987	42	51	27	**1997**	25	**2007**
1988	16	41	27	**2008**	28	**1978**
1989	13	10	29	**1972**	29	**2013**
1990	2	12	30	**1998**	30	**1973**
1991	34	50	31	**1983**	31	**2000**
1992	46	19	32	**2001**	32	**1976**
1993	19	47	32	**2006**	33	**1979**
1994	49	41	34	**1991**	34	**1972**
1995	19	7	34	**2004**	35	**1964**
1996	11	5	34	**2007**	36	**1982**
1997	27	25	37	**2000**	37	**2001**
1998	30	39	38	**1970**	38	**1970**
1999	10	21	39	**1967**	39	**1983**
2000	37	31	40	**1979**	39	**1998**
2001	32	37	41	**1968**	41	**1988**
2002	5	3	42	**1987**	41	**1994**
2003	21	41	43	**1965**	41	**2003**
2004	34	25	44	**1963**	44	**1963**
2005	1	6	45	**1980**	45	**1968**
2006	32	20	46	**1992**	46	**1965**
2007	34	25	47	**1986**	47	**1993**
2008	27	22	48	**1982**	48	**1981**
2009	4	17	49	**1973**	49	**1974**
2010	15	3	49	**1994**	50	**1991**
2011	26	18	51	**1981**	51	**1987**
2012	12	12	52	**1974**	52	**1975**
2013	25	29	53	**1984**	52	**1984**
2014	14	1	54	**1977**	54	**1980**
2015	3	14	55	**1975**	55	**1977**

Red and white wine consensus rankings between 1961 and 2015 by year (columns 1–3), by rank for reds (columns 4–5), and by rank for whites (columns 6–7). Rankings derived from sources in Table 1 following the procedure outlined in the text.

the whites include any years after 1994, demonstrating that the more recent decades have produced acceptable, if not excellent, wines from vintage to vintage.

As would be expected from generally known relationships between wine quality and climate (Jones, 2014), the top 10 red vintages tend to be warmer and drier during the growing season than the bottom 10 vintages (Table 3). The mean difference between the top and bottom 10 in growing season average temperature is 0.79°C, in GDD and HI is about 120 and 150, respectively, and for growing season rainfall is 102 mm. DTR is also higher for top 10 vintages and is linked to higher maximum temperatures rather than lower minimum temperatures, which were not significantly different between the top- and bottom-ranked vintages. Top 10 vintages were also affected by about one additional hot day (HD) and one fewer freezing day (FD) than average. The P–ET differences are also consistent with top-ranked vintages benefitting from warmer and drier conditions overall.

When examined by phenological stage, top red Burgundy vintages benefit from bud break period weather that is warmer and wetter than normal. Top 10 years have about 10 mm more precipitation than average, whereas bottom 10 vintages are 16 mm drier than average during the bud break phase. The ripening period is also especially important for reds, when warm and dry conditions are favorable. High daily maximum temperatures during the ripening period also drive higher DTRs, and both P–ET and total rainfall reflect hot and dry weather. Conversely, bottom 10 red vintages have 24 mm of additional ripening period precipitation than average, and the increased cloud cover lowers DTR.

Similar to the reds, the top 10 ranked white vintages are characterized by a warm and dry growing season; however, some of the differences are interesting (Table 4). The best white vintages are not necessarily unusually hot or dry, but the bottom 10 vintages are rather wet and cool. For example, over the growing season, T_{max} is only 0.2°C above average in the top 10

TABLE 3. Significant climate variables between top- and bottom-ranked red Burgundy vintages.

Variable	Mean (All Years)	Top 10 Red: Mean	Top 10: Departure from Mean	Bottom 10 Red: Mean	Bottom 10: Departure from Mean	P-value
Tmax (°C, gro)	20.8	21.4	0.6	20.1	–0.7	0.002
Tavg (°C, gro)	15.6	16	0.4	15.2	–0.4	0.010
DTR (°C, gro)	10.3	10.7	0.4	9.7	–0.6	0.001
P–ET (mm, gro)	–273.8	–356.7	–82.9	–206.2	67.6	0.010
Ptotal (mm, gro)	453	394	–59	496	43	0.028
FD (#of days, gro)	3	2	–1	4	1	0.011
HD (#of days, gro)	1	2	1	0	–1	0.045
GDD (C° units, gro)	1271	1341	70	1223	–48	0.041
HI (C° units, gro)	1743	1835	92	1683	–60	0.049
Tmin (°C, bud)	5.3	5.8	0.6	4.6	–0.7	0.016
Tavg (°C, bud)	10.4	10.9	0.5	9.5	–0.9	0.028
P–ET (mm, bud)	–25.8	–16.2	9.6	–38.5	–12.7	0.034
Ptotal (mm, bud)	46	56	10	30	–16	0.016
FD (#of days, bud)	2	1	–1	3	1	0.002
DTR (°C, blo)	10.7	11.3	0.5	10.1	–0.6	0.016
Tmax (°C, rip)	21.2	22	0.8	20.6	–0.7	0.049
DTR (°C, rip)	10.3	10.7	0.4	9.5	–0.9	0.019
P–ET (mm, rip)	–17.0	–32.2	–15.2	10.4	27.4	0.016
Ptotal (mm, rip)	64	52	–12	87	24	0.028

Comparison of the means for statistically significant variables across all years (column 2) as well as the top 10 (columns 3–4) and bottom 10 (columns 5–6) ranked vintages for Burgundy reds based on a Mann-Whitney test (alpha = 0.05).

Table 4. Significant climate variables between top- and bottom-ranked white Burgundy vintages.

Variable	Mean (All Years)	Top 10 White: Mean	Top 10: Departure from Mean	Bottom 10 White: Mean	Bottom 10: Departure from Mean	P-value
Tmax (°C, gro)	20.8	20.9	0.2	19.7	–1.1	0.001
Tavg (°C, gro)	15.6	15.7	0.1	14.9	–0.8	0.002
DTR (°C, gro)	10.3	10.5	0.2	9.6	–0.7	0.007
P–ET (mm, gro)	–273.8	–313.9	–40.1	–158.2	115.6	0.013
Ptotal (mm, gro)	453	417	–36	529	75	0.049
Pdays (#of days, gro)	89	83	–6	91	2	0.037
HD (#of days, gro)	1	1	0	0	–1	0.030
GDD (C° units, gro)	1271	1265	6	1136	–135	0.016
HI (C° units, gro)	1743	1723	20	1589	–154	0.028
Tmax (°C, blo)	22.8	23.3	0.5	21.3	–1.5	0.034
DTR (°C, blo)	10.7	11.2	0.5	9.7	–1.0	0.023
Pdays (#of days, blo)	10	8	–2	13	2	0.041
Pdays (#of days, ver)	8	8	0	5	–3	0.020
P–ET (mm, rip)	–17.0	–36.5	–19.5	42.1	59.1	0.005
Ptotal (mm, rip)	64	44	–20	118	55	0.003

Comparison of the means for statistically significant variables across all years (column 2) as well as the top 10 (columns 3–4) and bottom 10 (columns 5–6) ranked vintages for Burgundy whites based on a Mann-Whitney test (alpha = 0.05).

years but is 1.1°C below average in the bottom 10 ranked vintages. Similarly, the 10 lowest ranked vintages average 75 mm above normal rainfall in the growing season. Thus, excellent white vintages can be produced without an exceptionally favorable growing season climate.

Unlike reds, one of the key phenological stages for whites is the bloom period (Table 4). Top-ranked vintages have bloom periods with higher than average maximum temperatures and DTRs. Similar to reds, high-quality Burgundy whites have ripening periods that are dry. During the ripening stage, the poor vintages are characterized by excess rainfall (55 mm above normal) and a low P–ET (almost 37 mm below normal). It is also interesting to note that in the bloom period, good vintages have two fewer days of rainfall than normal whereas poor vintages have two additional days, but in the véraison period there were three fewer rain days in the bottom-ranked years.

A comparison of the key climate variables for reds and whites (Tables 3 and 4) exhibits some interesting differences. In general, top 10 red years are warmer, drier, have higher DTRs and more growing season heat accumulation than top 10 white years. For example, the mean HI for top 10 red vintages is over 110°C more than top 10 white vintages, and growing season rainfall is 23 mm lower. For all of the growing season variables, top 10 white vintages experienced a climate much closer to the mean than the top 10 red vintages. The main distinguishing factor for white Burgundy wine quality was the very poor climate conditions for bottom 10 vintages, which were characterized by cool and wet weather with growing season heat accumulation at least 10% below the mean value. The number of days with measurable growing season precipitation was a statistically significant factor for whites but not for reds, and top 10 white years averaged six fewer rain days than normal over the course of the growing season. With respect to the key phenological stages, the bud break phase climate appears to be more important for reds than whites, whereas the number of precipitation days during the bloom and véraison stages appears to be more critical for whites. Weather conditions during the ripening stage are important for both reds and whites, and top 10 white vintages are much drier during the ripening phase than top 10 red vintages.

Burgundy vintage quality rankings between reds and whites exhibit a linear relationship (Figure 2). The relatively small distance to the 1:1 line, especially for many of the top- and bottom-ranked vintages, indicates that years rated favorably for red wines also produced high-quality white wines. Five of the top 10 red vintages were also top 10 white vintages.

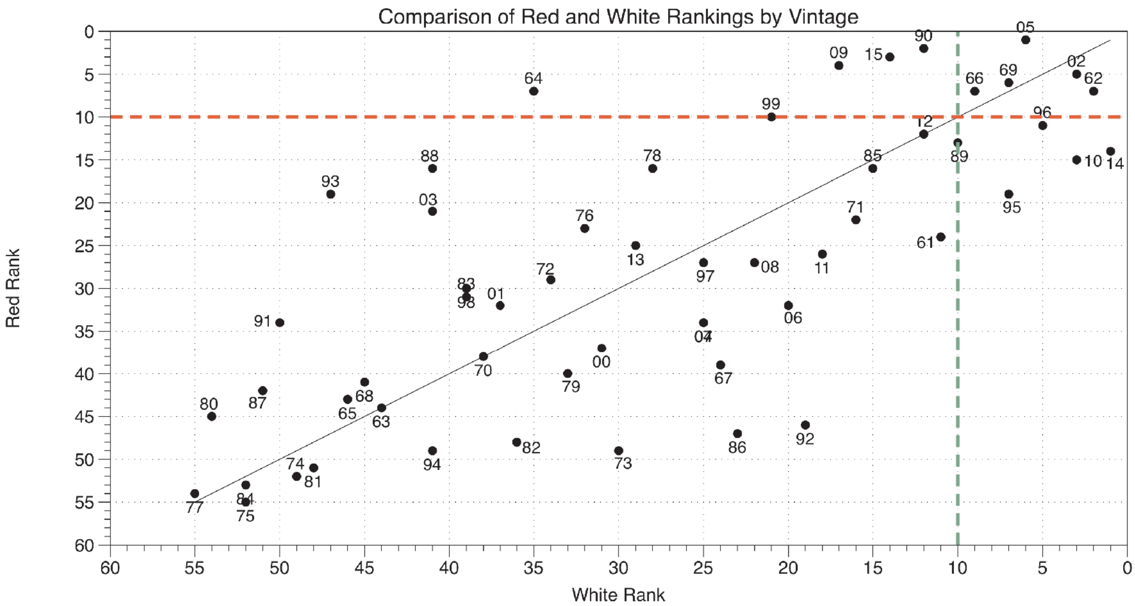

FIGURE 2. Comparison of Burgundy red and white vintage rankings.
The year of each ranking is labeled near the point. Dashed red and green lines identify the top 10 red and white vintages, respectively, and the 1:1 line is included for reference.

Similarly, poor-quality reds and whites tend to occur during the same year. The largest differences between red and white rankings in a given year were associated with neither exceptional nor poor vintages. The 1964 vintage is an interesting anomaly, as it was a great year for red Burgundy wines, tying for a rank of 7, but was only ranked 35th for Burgundy whites. Data for Chevalier Montrachet showed the 1964 vintage as having an unusually high pH, possibly because the grapes were harvested too late that year (Louis Latour Winery, personal communication).

Discriminant function analysis (DFA) was used to identify the key climate variables that best distinguish between top 10 and bottom 10 ranked vintages for both red and white Burgundy wines. For red wines, the first significant variable occurring in the DFA was the number of days with precipitation during the growing season (Table 5). However, six vintages were misclassified with P_{days} (gro) alone. Maximum temperatures during the ripening period were also significant, yet when used as a single discriminator left five vintages misclassified. The best single variable is growing season DTR, which correctly classified 85% of cases (Table 5 and Figure 3). Nine of the top 10 red vintages occurred when the average DTR (gro) exceeded 10.2°C. When the best second climate discriminator is added—the number of precipitation days during dormancy—19 of the 20 years are classified correctly (Figure 3). The two bottom 10 ranked vintages with growing season DTR above the cutoff are now properly classified with the addition of P_{days} (dor), as these vintages had a relatively low number of precipitation days during the dormancy period (Figure 3). Note, however, that P_{days} (dor) alone would be a poor discriminator between top and bottom reds, as the top-ranked red vintages had fewer dormancy precipitation days than bottom-ranked vintages. The unstandardized discriminant function is:

$$3.569\ DTR\ (gro) + 0.124\ Pdays\ (dor) - 45.14 = 0$$
(equation 3)

Using this 2-variable combination, only 1994 was misclassified (Figure 3). Since only one year is misclassified in the 2-variable model, a large number of potential 3-variable models would result in no misclassifications. The optimum additional variable is average maximum temperature during the ripening stage (Table 5). So in general, the key climatic factors that distinguish between top 10 and bottom 10 ranked red vintages are high DTR during the growing season with few days of precipitation in the preceding dormant period and higher than average daily maximum temperatures during the ripening period.

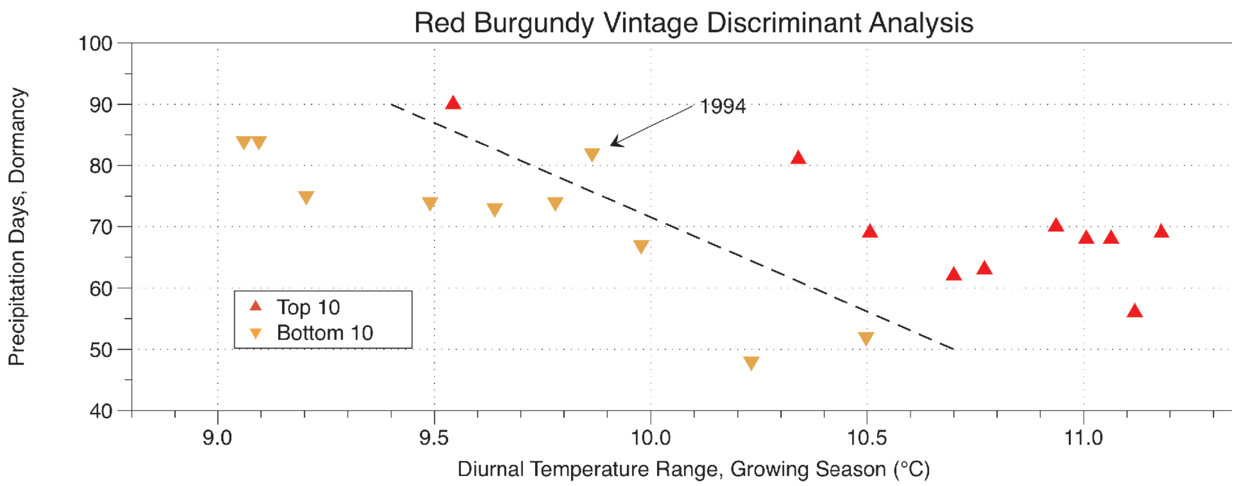

FIGURE 3. Two-variable discriminant plot for red Burgundy wines.
Discriminant function model using growing season DTR and dormancy precipitation days to classify Burgundy reds within either the top 10 or bottom 10 ranks. The dashed line is the discriminant function. The one misclassified year is labeled.

For white Burgundy wines, the best individual discriminator is average maximum temperature during the growing season (Table 5 and Figure 4). Using an average T_{max} (gro) threshold of 20.3°C, 90% of the top and bottom 10 vintages are correctly classified. With the addition of the number of rain days during the véraison phase, the 2-factor DFA correctly classifies all 20 years (Figure 4). The unstandardized discriminant function is:

$$1.721\ Tmax\ (gro) + 0.264\ Pdays\ (ver) - 36.63 = 0$$
(equation 4)

Note that a wet véraison period favors higher quality white Burgundy wines (Table 5), and this factor alone correctly classifies 75% of the vintages.

The importance of precipitation varies over the course of the growing season and differs for red and white wines (Figure 5). During the bud break period, both reds and whites appear to benefit from early season rainfall, and the top vintages have nearly double the precipitation of the bottom vintages. However, bloom period precipitation appears to have little impact on red wine quality. Conversely, the poorest white vintages had a very wet bloom stage. The amount of precipitation during the véraison stage was not as important for white wines as for reds; however, whites benefitted slightly from more véraison stage rainfall in contrast to red wines, in which poor red vintages experienced a much wetter véraison period than good vintages. Finally, a dry ripening period benefits both red and white Burgundy wines.

To explore further the difference between red and white rankings within a given vintage, a final DFA was run based on the difference between the red and white rankings for each year. One group included the top 10 years in which reds were ranked much higher than whites, and the second group included the 10 years in which white Burgundy wines were ranked much higher than reds. The DFA identified a single variable as the best discriminator between the two groups—precipitation during the véraison period. In the top 10 years when whites were more highly ranked than reds, véraison stage rainfall averaged 60 mm; when reds were much more highly ranked than whites, rainfall was 28 mm. Using only this variable, the classification was correct 75% of the time.

DISCUSSION

Climatic conditions differ markedly between the top- and bottom-ranked Burgundy vintages for red and white wines, both throughout the growing season and for specific growth stages of the plant. Many of the climate variables examined in this study demonstrate statistically significant differences between top- and bottom-ranked vintages, but because many of these variables are highly correlated with each other, they represent similar climatic conditions. In general, a highly ranked vintage is more likely to occur from a warm growing season that has

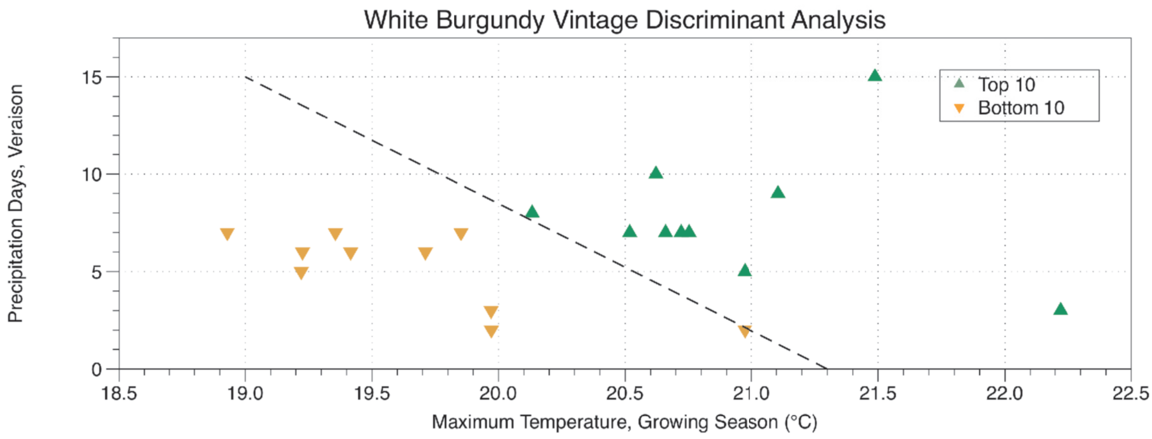

FIGURE 4. Two-variable discriminant plot for white Burgundy wines.
Discriminant function model using growing season T_{max} and véraison period precipitation days to classify Burgundy whites within either the top 10 or bottom 10 ranks. The dashed line is the discriminant function. All years are correctly classified using this model.

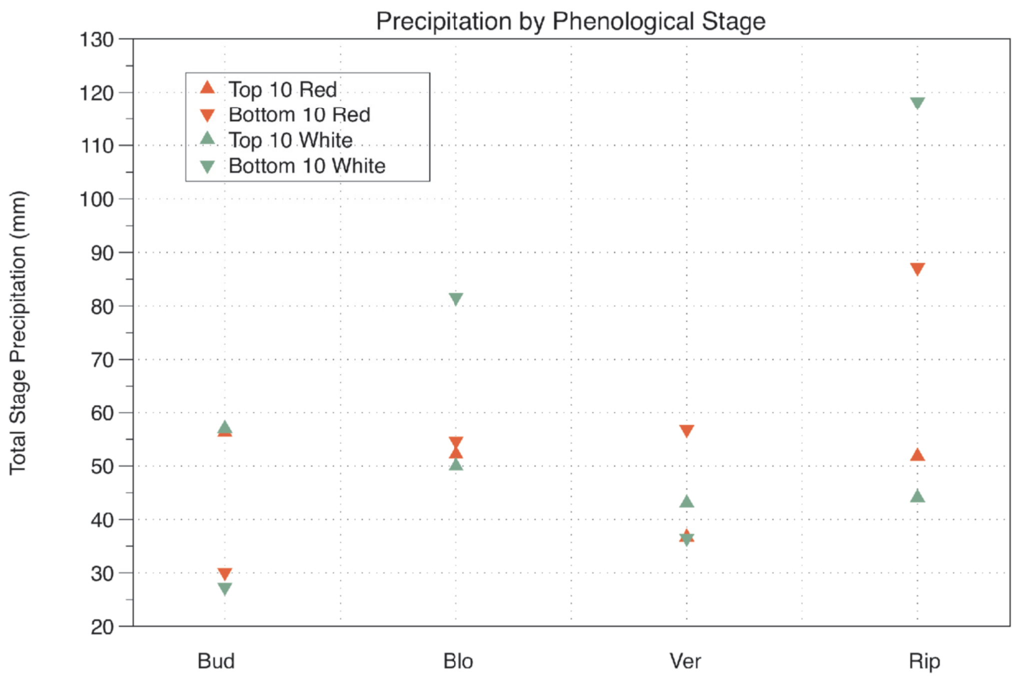

FIGURE 5. Average precipitation by phenological stage for top- and bottom-ranked red and white Burgundy wines.

higher than average heat accumulation (GDD and HI), little rainfall (especially in the latter half of the growing season), and clear skies. Lack of cloud cover is generally associated with high daytime maximum temperatures and cool nights, resulting in a high diurnal temperature range (DTR). Under these conditions, P–ET is strongly negative during top vintage growing seasons, since evapotranspiration is mostly dictated by high temperatures and the plants are growing in a state of moisture stress or deficit. Despite the consistent importance of T_{max} and DTR, T_{min} is not generally an important variable (only for reds during the bud break phase), which suggests it is high maximum temperatures that are driving the DTR relationships rather than low nighttime minima.

The importance of rainfall varies according to phenological stage and differs for red and white wines. Both reds and whites benefit from above normal rainfall during the bud break period. The best red vintages are characterized by below normal rainfall in the latter half of the growing season. White Burgundy wines are more greatly impacted by rainfall in the ripening stage, as many of the poorest-ranked white vintages had high late season precipitation totals. During the bloom period, the rainfall difference between top 10 and bottom 10 white wine vintages is large, whereas the difference for reds is negligible. Furthermore, the amount of rainfall received during the véraison stage is the best determinant of years in which there is a large disparity between red and white rankings, with more rainfall favoring higher quality white vintages and poorer red rankings. In general, over the course of the growing season, variations in the distribution of rainfall have a greater impact on the overall quality of white wines than for red wines in Burgundy.

Growing season diurnal temperature range was the best single discriminator between top- and bottom-ranked Burgundy red vintages, correctly classifying 85% of cases (Table 5). For white wines, growing season average maximum temperature was the best individual discriminator, as 90% of cases were correctly classified by this single variable (Table 5). The misclassified vintages can provide some interesting case studies. For example, 1991 was misclassified as a top 10 year for white Burgundy wines based on the T_{max} (gro) model. Overall, the growing season was warmer and had more heat accumulation than the mean of the top 10 years. However, the véraison period was unusually dry (recall that whites benefit from more véraison stage rainfall) but the ripening period was very wet, with 126 mm of rainfall (the mean of the bottom 10 white vintages is 118 mm). Thus, what would likely have been an excellent vintage was thwarted by an adverse rainfall distribution in late summer. Furthermore, the ripening phase in 1991 was heterogeneous because of damage arising from a late spring frost. In contrast, 1996 had comparatively low heat accumulation over the growing season, values well below the mean of top 10 white vintages. However, there was adequate rain during the véraison phase, and the ripening period was very dry, with only 50% of the precipitation observed relative to the average top 10 year. Thus, the 1996 crop was salvaged, despite comparatively low temperatures, by very favorable weather prior to harvest.

One of the benefits of a climatically favorable growing season is that it can allow the producer to carefully select harvest time. In an attempt to examine this, we used harvest dates (start, average, and end of harvest) for Domaine Louis Latour (Bois, 2013) and compared the top- and bottom-ranked vintages (consensus rankings) for both reds and whites. The top 10 vintages had

TABLE 5. Climate discriminators between top- and bottom-ranked vintages.

Discriminator(s)	Correctly Classified (%)	Number of Misclassifications	Poor Years Misclassified as Good	Good Years Misclassified as Poor	Cut Point
Red: P_{days} (gro)	70	6	1973, 1982, 1984	1999, 2002, 2005	86.6 days
Red: T_{max} (rip)	75	5	1973, 1982	1990, 2002, 2015	21.3°C
Red: DTR (gro)	85	3	1973, 1992	1966	10.2°C
Red: DTR (gro) and	95	1	1994	0	-
Red: DTR (gro), P_{days} (dor), and T_{max}	100	0	0	0	-
White: P_{days} (ver)	75	5	1965, 1975, 1977	1989, 2005	6.5 days
White: P_{total} (rip)	85	3	1977, 1980	1995	83.1 mm
White: T_{max} (gro)	90	2	1991	1996	20.3°C
White: T_{max} (gro) an	95	1	1991	0	-
White: T_{max} (gro) an	100	0	0	0	-

*Shown in Figure 3 - **Shown in Figure 4

Combinations of key discriminators using DFA between Burgundy top 10 and bottom 10 vintages (column 1), model performance indicators (columns 2–3), and misclassified years (columns 4–5). The cut point (column 6) is the value of that climate variable that best discriminates between top and bottom 10 ranked years for the single predictor models.

average harvest dates 5–9 days earlier for reds and 2–3 days earlier for whites. Although the differences were not large enough to be statistically significant, these results are consistent with expectations that hang-time is correlated with achieving higher vintage quality. In cool and sub-humid wine producing regions such as Burgundy, bunch rot can advance the harvest date of unripe grapes. Molitor *et al.* (2016) observed in Rheingau (Germany) that the timing of bunch rot epidemics was correlated with vintage quality for Riesling white wines (the later the development of *Botrytis cinerea*, the higher the vintage quality). Bunch rot epidemic onset was correlated with warm and dry conditions around blooming, leading to excellent fruit set and therefore more compact grapes that favor the development of *Botrytis cinerea*. Our analysis for Burgundy showed that white wines benefitted from a warm and dry bloom period with a high DTR. Further research would be needed to determine if this relationship is indeed related to bunch rot timing in this region.

It is important to note that many of the weather variables are highly correlated. For example, although T_{max} (gro) was selected as the single best white wine discriminator, one could get very similar results using T_{avg}, HI, or GDD. Therefore, once a temperature-based variable was selected as the most important primary discriminator, it is highly unlikely that the secondary discriminator would also be correlated with temperature.

No dormancy period variables differed significantly between top 10 and bottom 10 vintages for either red or white Burgundy wines. This is in contrast to results from Bordeaux, where cool, moist winters that preceded warm, dry summers with a larger diurnal temperature range during the growing season were generally associated with high quality wines (Jones & Davis, 2000). Despite the lack of overall significance, the number of precipitation days during the dormancy period was the secondary discriminator in the model that correctly classified 95% of red vintages (Table 5).

By carefully monitoring climatic conditions throughout the growing season, it may be possible to better anticipate the likelihood of a great vintage prior to harvest. Although sub-optimal late season weather can always devastate a promising crop, the die is often cast well before harvest based upon heat accumulation, and especially high maximum temperatures, coupled with the appropriate distribution of growing season rainfall. Using this type of climate data, it should be possible to mathematically model the probability of an exceptional vintage by mid-summer.

The importance of this research is magnified when considering climate change and the potential impacts to both viticulture and wine production (Jones *et al.*, 2005; Bois, 2013). As a result of warmer climates in wine regions globally, changes in grapevine growth events have been documented with earlier bud break, bloom, véraison, and harvest dates seen in wine regions worldwide (Jones, 2014). One result is that many regions are seeing ripening that is occurring in a hotter period of the summer, resulting in a greater disconnect between sugar accumulation, acid respiration, phenolic ripeness, and the development of fruit character (Soar *et al.*, 2008; Jones, 2014). Furthermore, a warming growing season could push Burgundy beyond the optimum conditions for the varieties currently being grown in the region (Jones *et al.*, 2005).

It would be interesting in future research to compare the rankings of individual raters and climate variables to the consensus rankings used here. In this research, we implicitly assume that the consensus ranking provides a useful assessment of the quality of a given vintage and that this ranking has no inherent error. While it is beyond the scope of this research, it would be possible to compare how the consensus is impacted by dropping or adding individual raters to determine how influential a single data point might be on the resulting consensus. This kind of error analysis should add confidence in the usefulness of a consensus approach to vintage ratings. Furthermore, our analysis did not include extreme events, such as hail, unusually late spring or early autumn frost, or floods. Although these conditions could influence overall vintage quality, they are more likely to impact variability in grape production. These results were derived from, and thus specifically apply to, Burgundy vintages. The extent to which these relationships are generalizable to other viticultural regions is a topic for future research. Finally, our analysis used fixed dates to define the phenological periods. With more detailed phenological information for each vintage, in time and space, the climate factors could be honed more precisely, and these finer estimates might provide further insight into fundamental climate/viticulture relationships.

CONCLUSIONS

Using consensus rankings of Burgundy vintages from 12 credible and widely-cited wine evaluation sources, we find consistent climatic factors between top 10 and bottom 10 ranked vintages in Burgundy. Good vintages have warm and dry growing seasons that are characterized by a large diurnal temperature range. Red Burgundy wines benefit from a warm and relatively wet bud break period and warm but dry weather during the ripening period. In contrast, the climate associated with top white Burgundy wines is not especially unusual, but the poorest-ranked vintages are particularly cool and wet. Overall, the best single climatic discriminator between top- and bottom-ranked red vintages is high diurnal temperature range over the growing season, whereas the best white discriminator is growing season maximum temperature. For both red and white Burgundy wines, conditions at early stages in the grape's phenological cycle have some influence on the ultimate ranking of the vintage. This within growing season relationship between phenology, climate, and rating suggests that wine futures markets could benefit from carefully tracking daily weather conditions and the vine's phenological stages. However, the key climatic factors and the best overall discriminators between good and poor vintages are variables that are measured over the entire growing season, so weather conditions during early season phenological stages are ultimately of marginal importance in Burgundy.

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