

Climate Influences on Grapevine Phenology, Grape Composition, and Wine Production and Quality for Bordeaux, France

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A long-term (1952–1997) climatology was developed using reference vineyard observations in Bordeaux, France. The procedure partitioned the season into growth intervals from one phenological event to the next (budburst, floraison, veraison, and harvest) in which climatic influences were summed and assessed. The data were then used to investigate the relationships between climate and phenology, berry composition at harvest, total production, and quality. Over the last two decades, the phenology of grapevines in Bordeaux has tended towards earlier phenological events, a shortening of phenological intervals, and a lengthening of the growing season. Merlot and Cabernet Sauvignon varieties have tended to produce higher sugar to total acid ratios, greater berry weights, and greater potential wine quality. Vintage ratings have shown a general increase over the last two decades paralleling the observed phenology and composition trends. The composition and quality trends were mostly described by increases in the number of warm days during floraison and veraison and a reduction in precipitation during maturation. Production variability was not as readily described by phenological-interval climate parameters, but regression modeling did indicate that rainfall during physiologically important periods (flowering and maturation) tended to decrease crop production. By variety, the relationships between phenology, climate, and composition were typically higher (both positive and negative) for Merlot than for Cabernet Sauvignon and could be an indication that, in Bordeaux, Merlot is more phenologically and climatologically sensitive. Additionally, sugar to acid ratios revealed that both Merlot and Cabernet Sauvignon composition influenced Bordeaux wine quality, although variations in Cabernet Sauvignon described substantially more of the variability in ratings. This indicates that the wine industry in Bordeaux is more dependent on Cabernet Sauvignon for good vintages than on Merlot.

KEY WORDS: *Vitis vinifera*, grapes, grapevines, phenology, composition, quality, climate

Grapevines are grown in distinct climate regimes worldwide that provide ideal situations to produce high quality grapes [9]. One region where this is evident is in Bordeaux, France, a grape growing area that is synonymous with some of the best wines in the world. While the interactions between the local climate, soil, and site location (termed the “*terroir*” by the French) play a varied role in the ontogeny and yield of the grapevines, the *general* effect of climate is known. Mild to cool and wet winters followed by warm springs, then warm to hot summers with little precipitation provide adequate growth potential and increase the likelihood of higher wine quality [7,10,16,19,42 and others]. Therefore, there is an optimum seasonal climate regime that contributes greatly to the overall quality of a given vintage.

Occurring as a direct effect of climate, the grapevine’s growth can be described by its phenological events. Understanding the phenology of a given plant system is important in determining the ability of a region to produce a crop within the confines of its climatic regime [6]. From a husbandry viewpoint, knowledge of a plant’s growth stages is advantageous as cultural and chemical practices can be applied at optimum times in a plant’s annual growth cycle. Additionally, information regarding growth stages can be useful in estimating crop yields.

Vitis vinifera grapevines are a phenologically distinct crop with the most important developmental stages being débourrement (budburst), floraison (flowering), veraison (color change and maturation nascent), and harvest (grape maturity). The time between these phenological stages varies greatly with grapevine variety, climate, and geographic location. In regions with cool climates and short growing seasons, early-ripening varieties are necessary whereas in hot climates, late-ripening varieties have enough time to achieve full maturation. The timing of these developmental stages is also related to the ability of the vine to yield fruit, with early and fully expressed phenological events (*i.e.*, adverse weather during floraison would disrupt the event) usually resulting in larger yields [19,31]. Additionally, phenological timing has been related to vintage quality with early harvests generally resulting in higher quality vintages [19,37].

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Acknowledgements: The climate data for this research were made available through a Moore Research Grant from the Department of Environmental Sciences at the University of Virginia. Numerous individuals and organizations in France must be commended for their help in securing the climate and viticulture data used in this study: METEO-France, the University of Bordeaux II and Professors P. Ribéreau-Gayon and G. Guimberteau, Anne Marbot, and Kelly O’Connor at the Conseil Interprofessionnel du Vin de Bordeaux, and Henry LeMay at Editions Féret. Special thanks is extended to Bruno Prats (formerly of Cos d’Estoumel) for providing the inroads and insight into the viticulture industry in Bordeaux. We also thank the AJEV reviewers for their helpful comments and suggestions that greatly improved the manuscript.

Manuscript submitted for publication 16 August 1999; revised 24 January 2000.

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Many studies examining the relationships between climate and grapevine growth, berry composition, production, and quality have employed monthly averages or growing season (April-October) summations in temperature and precipitation as the independent variables [for a good review, see 16]. In addition, most studies that look at these relationships are derived from short-term data sets (usually 10 years or less) or from trials over a few seasons and often only examine one or two phenological events [13,40, and others]. Given that plants do not respond to a calendar division of climate data, and that phenological timing, production, and quality are related [19], it would seem appropriate to develop a baseline climatology using the major grapevine phenological events to identify the stages in which climate has pronounced effects.

Therefore, the goal of this research was to develop a long-term daily phenological-interval climatology to study climate's effect on grapevines. Unique to this study was a division of the year into "physiologically correct seasons" as dictated by the plants (*i.e.*, a variable interval determined by plant physiology rather than some arbitrarily fixed set of intervals determined by calendar dates). The method provided a more comprehensive examination of when, during the growth intervals, climate elements have the greatest impact on grape growth and production. The research utilizes two data sets containing long-term grapevine phenology, composition, production, and vintage ratings, along with local weather data from Bordeaux, France to develop a climatology from which mid-season, yearly, and long-term assessments of the relationships can be made.

Materials and Methods

Viticulture: In the Bordeaux region, long-term phenological observations have been kept by many châteaux, including some harvest date records from the sixteenth century [25,33,34,36]. However, due to changes in ownership, poor record keeping, and a general uneasiness of sharing data, long periods of records that include multiple phenological events are not readily available for the region as a whole. In the early 1950s, the University of Bordeaux started recording the phenology, composition, and overall vintage ratings from 10 to 15 of the top châteaux in the region (the names of the châteaux are confidential and known only by the châteaux and the data collectors) and are reported each year in vintage summaries [37]. The phenology and composition observations are made for the two main varieties grown in the Bordeaux region — Cabernet Sauvignon and Merlot — and the rating is an overall vintage assessment for the reference vineyards.

The phenological data from these reference vineyards are for the average dates (averaged between châteaux and variety) of floraison, veraison, and harvest for 1952 to 1997 (Table 1). The floraison and veraison events are considered to occur when, for a given varietal, 50 percent of the plants are exhibiting the physiological response. Harvest date is recorded as the point at which, due to the optimum sugar levels, the harvest commences. This phenological record does not contain observations for budburst. To include this important phenological stage and to provide a better division of the growth cycle of the grapevines, a simple model was employed to derive a budburst date. Amerine *et al.* [1] and Mullins *et al.* [31] stated that for

Table 1. Bordeaux reference vineyard phenology, production, composition, and quality descriptive statistics for Cabernet Sauvignon and Merlot varieties.

Variable	N	Mean	Std. Dev.	Max	Min	Range
Budburst (estimated, days)	49	23-Mar	18	24-Apr	9-Feb	75
Floraison (days)	46	12-Jun	8	27-Jun	23-May	35
Veraison (days)	46	17-Aug	9	3-Sep	31-Jul	35
Harvest (days)	46	2-Oct	9	17-Oct	3-Sep	44
Budburst to Floraison (days)	46	81	18	139	51	88
Budburst to Veraison (days)	46	148	19	206	115	91
Budburst to Harvest (days)	46	193	19	246	162	84
Floraison to Veraison (days)	46	67	3	76	60	16
Floraison to Harvest (days)	46	112	6	125	103	22
Veraison to Harvest (days)	46	45	5	58	34	24
Cab. Sauvignon TA (g/L)*	26	5.2	1.0	8.2	3.8	4.4
Cab. Sauvignon sugar (g/L)	26	190	11.3	214	168	46
Cab. Sauvignon wt/100 berries (g)	26	120	13.1	162	104	58
Merlot total acidity (g/L)*	26	4.6	0.9	7.2	3.2	4.0
Merlot sugar (g/L)	26	203	13.7	232	176	56
Merlot weight per 100 berries (g)	26	147	17.6	186	120	66
AOC red wine production (hL/year)	60	2085020	1532183	5748688	370978	5377710
Quality (scale 1-7)	57	4.7	1.9	7	1	6

*Total Acidity is measured in grams of H₂SO₄ per liter.

most viticultural regions, on average, budburst starts to occur when the mean daily temperature exceeds 10°C for five consecutive days. Therefore, for each year, 1949 to 1997, the mean daily temperature was compiled and analyzed. The first occurrence of five consecutive days of mean daily temperatures greater than 10°C that was *not* followed by a series of five or more days with mean temperatures lower than 10°C, or by any notable period of variable but prolonged cold, was identified. Budburst was then considered to occur on the sixth day. While estimation of the budburst date from temperature data may not exactly coincide with the region-wide mean occurrence of budburst, the method produced values consistent with site-specific observations of budburst for two châteaux ($r = 0.72$ and $r = 0.68$, Châteaux Latour and Lafite, respectively, [14,17,36]) and in the absence of region-wide observations provided a reasonable estimate.

In addition to the phenology, grape composition (1970-1997) and wine quality ratings (1940-1995) have also been tabulated from the evaluation of the reference vineyards [11,37]. Near harvest time, the key vintage quality characteristics are the chemical composition of the grapes. Two of the chief determinants of crop ripeness and quality are the relative amounts of sugar and acid found in the berries leading up to harvest [31]. While the production of wine in Bordeaux consists of a blend of from two to four different red varieties, Merlot and Cabernet Sauvignon account for over 80% of the grapes grown in the region¹ [5]. Although the relative percent of the two grapes varies spatially within the Bordeaux region, it is their relative variability in composition that largely influences the quality of the vintages. Acid and sugar levels, along with berry weights, are measured at the reference vineyards just prior to harvest and are averaged to obtain a single value for each vintage and variety for 1970 to 1997 [37].

Vintage ratings for Bordeaux have been compiled over various time periods by a wide variety of sources [e.g., 3,32,33]. While any qualitative assessment of a vintage is a generalization, ratings commonly serve as the industry-wide benchmark by which vintages are compared. The overall vintage quality rating for the reference vineyards (1940-1995) used in this study is scaled from 1 to 7 with 1 being a terrible year and 7 an exceptional year [37] (Table 1). While quality ratings are inherently subjective and do not consider variations in quality among the individual châteaux, their relative measure, especially when tabulated in a consistent manner (as are these data), gives a reliable quality variable with which to assess general climatic influences.

Production data for the reference vineyards are not recorded in a manner consistent with the other data

used in this analysis (*i.e.*, from the reference vineyards). To examine the effect that phenological-interval climate variations play on production levels, Bordeaux region data were obtained from the Conseil Interprofessionnel du Vin de Bordeaux [CIVB, 5]. The CIVB is an agency that acts as a liaison between the growers of the region and the consumer and maintains the most reliable and comprehensive data on region-wide production, acreage planted, and yield for the region. Data used in this analysis consist of the production² of Appellation d'Origine Contrôlée (AOC) red wines (wines from the highest quality designated producers) for 1938 to 1997. These data most closely match those regions and châteaux from which it is assumed that the reference vineyard data are observed.

In most agricultural systems, there is a noted increase in the yield of the crop over time due to technological advances in husbandry and mechanization [41], and viticulture is no exception [1,18,31]. Gladstones [16] found that, after accounting for technology, climate is the main control on the yield of the grapevine. To determine the relationship between the quantity of the harvest and climate, the production data were detrended using the most appropriate estimator (linear, quadratic, *etc.*) [30]. This method developed an equation that best fitted the trend in the production (dependent variable) over time (independent variable) and allowed for the calculation of a "predicted" time series. The observed values of production were then subtracted from those predicted by the equation to form a time series of residuals. Any technological increasing or decreasing production trend was therefore accounted for and the remaining residuals were related to climatic variations.

Climate: Climate data used in this analysis are for the Bordeaux station for 1949 to 1997 and were obtained from METEO-France [29]. The weather station is located at 44°49'N and 00°41'W at an elevation of 47 meters to the southwest of the city Bordeaux and has not been relocated over the period of record. The data consist of daily observations of maximum temperature (T_{\max}), minimum temperature (T_{\min}), hours of insolation, and precipitation. These general climate parameters were used to derive other variables commonly used in viticulture studies in the region, including;

- The Sum of Average Temperatures ($SAT = (T_{\max} + T_{\min})/2$). While there are numerous accumulated heat indices used to evaluate grapevine parameters (growing degree-days base 10°C is most common, see 8,16,38 for good reviews), SATs were used in this analysis since they are commonly used in Bordeaux. The correlations between SATs and growing degree-days (base 10°C, are between 0.91 and 0.97 over the growing season stages.
- Estimated Potential Evapotranspiration ($PET = SAT - \text{precipitation}$). The PET variable is a composite

¹ For the Bordeaux reference vineyard data used in this study, no mention is given to whether the composition data are from the same clones for each varietal. Given that this study's focus is to develop a general phenological-interval climatology, and since the phenology and composition data are from the same reference vineyards, the compositional variability between clones is assumed to be minimal.

² While yield variations would be more representative of climate-induced variability, AOC red wine acreage data is limited in the CIVB publications, leaving production to be examined in the analysis.

index, often used in Bordeaux, in which temperature and rainfall are considered simultaneously (units are not normally given) and is referred to as the Ribéreau-Gayon and Peynaud Index.

- The number of days with extreme cold. This is the number of days with minimum temperatures less than -2.5°C and the number of days with minimum temperatures less than -10°C, thereby creating two variables that allow for the assessment of both moderate and extreme cold events.
- The number of days with high temperatures. Similarly, the number of days with maximum temperatures greater than 25°C and the number of days with maximum temperatures greater than 30°C for the assessment of both moderate and extreme warm events.

Although numerous other climate parameters, including many bioclimatic indices [15,38] and average temperatures [13], could have been used in this analysis, the variables chosen roughly reflect those historically employed for the area and region [37].

Each vintage (from the end of harvest in one year to the beginning of harvest in the next) in the Bordeaux region was divided according to the major phenological events of budburst, floraison, veraison, and harvest, thereby creating four intervals based upon the grapevine's annual growth cycle:

- Dormant Interval – from the commencement of harvest of one year to budburst of the next (dormancy is normally considered from leaf fall to budburst; however, since leaf fall is not observed for the reference vineyards, the date of harvest is used).
- Budburst Interval – from budburst to flowering.
- Floraison Interval – from flowering to veraison
- Veraison Interval – from veraison to harvest

The climate data were summed by day and phenological interval using the estimated budburst and mean phenology of the grapevines from the reference vineyards [19]. SAT, PET, precipitation, hours of insolation, and days with extreme cold or warmth provided up to eight independent climate variables per interval for the analysis. Although there were potentially 32 climate variables, some intervals did not experience days with temperatures below -2.5°C and/or -10°C; therefore, 27 independent climate variables were used in the analysis. In examining the relationships between phenological-interval climate and viticulture variables, all climate variables that occurred in the intervals before a given

event were included. For example, all climate variables of the dormant, budburst, and floraison intervals were used to model the date of veraison. Similarly, all 27 climate variables were used to model wine quality.

Multiple regression procedures were used to relate the viticulture (dependent) variables (phenology, production, must composition, and vintage ratings) to the climate (independent) variables (summed by phenological interval). To achieve an optimum set of models in the statistical analysis, a two-stage “all-possible combinations” regression method was employed. As opposed to step-wise methods of regression analysis, the all-possible combinations method allows the user to assess all possible combinations of variables instead of just the final model derived from the stepping procedure. It has been found that the step-wise method often does not identify the optimum statistical model [19]. The first stage used a procedure that determined the combination of variables that produce models with the highest coefficient of determination (adjusted R²). This procedure found the best one through n-variable models for the climate-viticulture relationships. The “adjusted R²” statistic was used because it minimizes the inflated R² values that frequently occurs in models with low degrees of freedom [12]. The second stage determined which suite of n-variable models best described the relationship for each independent variable [22].

For the all-possible combination procedure, variance inflation factors (VIFs) were used to determine if severe collinearity occurred between the variables

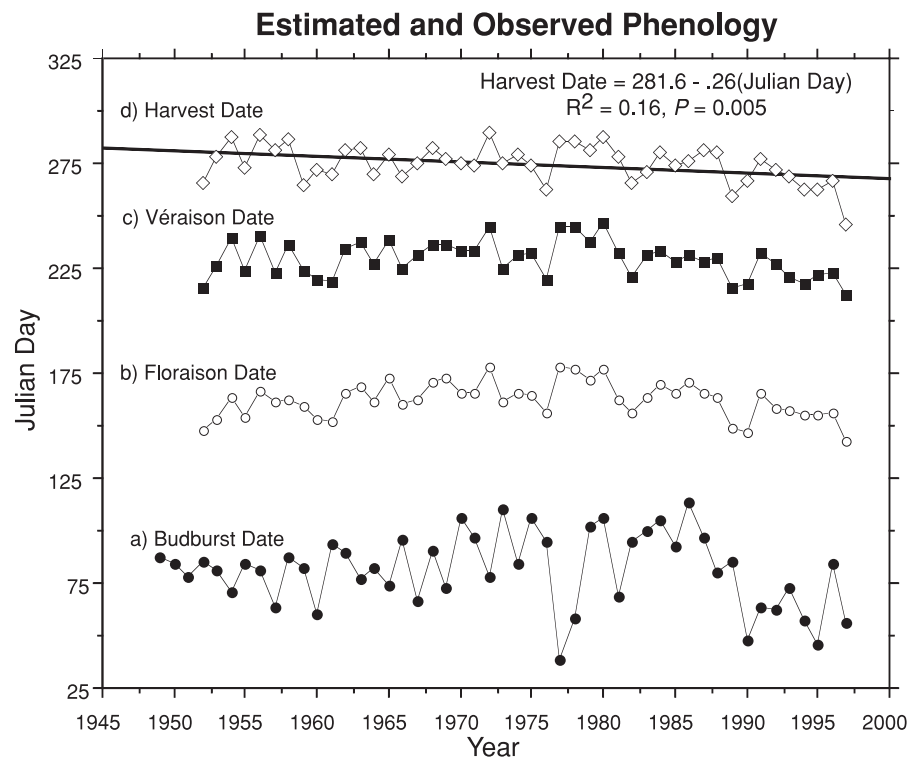


Fig. 1. Time series of the major phenological events for the Bordeaux reference vineyards (budburst is estimated as described in the text). Harvest date is the only series that had a significant trend for the time period.

[12,39]. High VIFs indicated that two or more collinear variables were in the model (*e.g.*, a strong positive correlation between SAT and PET). Then, the procedure removed the variable from the model that explained less of the variance in the dependent variable. The criteria for the final model selected included a significance level of 0.05 and $VIF < 2.00$ [39]. Additionally, regression diagnostics and residual plots were examined to insure quality control in the analysis.

Results and Discussion

Phenology: For the Bordeaux region, the mean derived budburst date was 23 March and the standard deviation was 18 days (Table 1). The time series showed an earlier occurrence of budburst in the later part of the record that was consistent with the trends in the observed phenological dates (Fig. 1a). The mean date of floraison was 12 June and ranged from 23 May to 27 June (Table 1). Advanced flowering occurred in both the early and later periods of the record, with relatively delayed flowering during the mid-1960s through the early 1980s (Fig. 1b). Veraison occurred as early as 31 July, as late as 4 September and on 17 August on average (Table 1). The time series of the date of veraison displays a large degree of annual variation with generally later dates in the 1970s and earlier dates in the 1980s and 1990s (Fig. 1c). The average harvest date for the region was 2 October, although it commenced as late as 17 October and as early as 3 September (Table 1). The 3 September 1997 harvest date is the earliest recorded during the period and is one of the earliest in long term records of harvest dates in the region [24,25,37]. For the period of record, harvest date was the only phenological event that displayed a significant relationship to Julian day and showed that harvest dates were nearly 13 days earlier than in the 1950s (Fig. 1d). The trend might be due to warmer growing season conditions but could, in part, be due to a recent tendency for vintners to harvest earlier [J.-P. Valette, 1996, personal communication].

Often more important than the actual date of each phenological event is the interval between events, which gives an indication of the overall climate during those periods. Short intervals are associated with optimum conditions that facilitate rapid physiological growth and differentiation [6,28]. Long intervals between events indicate less than ideal climate conditions and a delay in growth and maturation [4,16]. One of the more important intervals is the length of the growing season (from estimated budburst to harvest), and was found to average 193 days (± 19 day SD). Growing season length ranged from 162 days in 1986 to 246 days in 1977. Three of the intervals showed significant decreasing trends over time indicating earlier grapevine physiology in the region. The interval from floraison to veraison averaged 67 days (± 3 day SD) and showed a four-day decrease over the period of record (Table 1, Fig. 2a). The average period of time from flowering until harvest was 112 days (± 6 day SD) and was nearly 10 days earlier at the end of the time series (Table 1, Fig. 2b). The time from veraison through

harvest averaged 45 days (± 5 day SD) and decreased by nearly 6 days from 1952–1997 (Table 1, Fig. 2c).

The grapevine phenology observations in Bordeaux

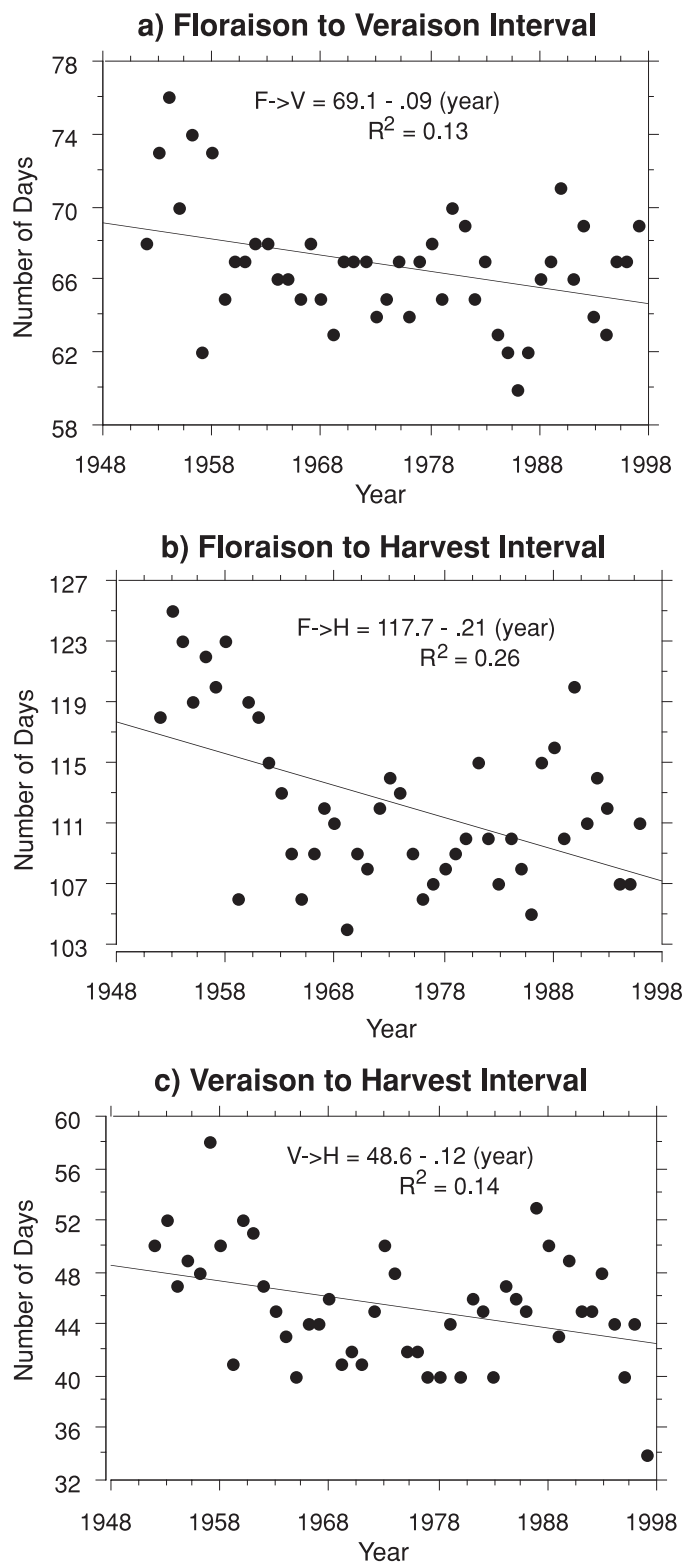


Fig. 2. Significant trends of the intervals between phenological events for: (a) floraison to veraison, (b) floraison to harvest, and (c) veraison to harvest. The trend equation and explained variance are inset.

Table 2. Pair-wise correlations between phenology (1952-97), composition (1970-97), production (1938-1997), and quality (1940-95) for the Bordeaux reference vineyards.

Variables	Bud-break	Floraison	Veraison	Harvest	Cab. Sauv. acid	Cab. Sauv. sugar	Cab. Sauv. wt	Merlot acid	Merlot sugar	Merlot wt	AOC red prod.	Quality
Budburst	1.00											
Floraison	.20	1.00										
Veraison	.10	.93**	1.00									
Harvest	.14	.80**	.87**	1.00								
Cab. Sauv. acid	.03	.57**	.60**	.59**	1.00							
Cab. Sauv. sugar	.14	-.38*	-.37*	-.45*	-.57**	1.00						
Cab. Sauv. weight	-.28	-.45**	-.49**	-.51**	-.21	.13	1.00					
Merlot acid	.05	.74**	.77**	.72**	.91**	-.54**	-.29	1.00				
Merlot sugar	.15	-.38*	-.34*	-.39*	-.59**	.91**	.02	-.62**	1.00			
Merlot weight	-.39*	-.44**	-.45**	-.40*	-.25	-.06	.80**	-.29	-.048	1.00		
AOC red production	.20	-.34*	-.34*	-.31*	-.24	.30	-.18	-.31*	.33*	-.32*	1.00	
Quality	.23	-.47**	-.55**	-.65**	-.83**	.85**	-.15	-.77**	.80**	-.10	.31*	1.00

Note: * and ** denote a correlation that is statistically significant at $\alpha = 0.05$ and 0.01 levels, respectively.

are in agreement with an observed lengthening of the growing season in Europe of nearly eleven days over the last 30 years for many species in the International Phenological Garden (IPG) network [27]. Furthermore, Bindi *et al.* [2], comparing different models of future climate change for Italy, indicate a composite 23-day reduction in the interval from budburst to harvest for Cabernet Sauvignon and Sangiovese grapes due to increased CO₂ and temperatures. While it is clear that climate change adaptation in phenology and yield be-

tween varieties and viticultural regions will occur [23], a longer and warmer growing season will bring greater ripening potential, and therefore greater potential wine quality, to Bordeaux.

A high correlation exists between individual phenological dates, with each event being highly correlated with the one directly preceding it (Table 2). These observations indicate that growth intervals were fairly constant regardless of the weather conditions during the growing season (*i.e.*, a one day early or delayed

Table 3. Regression model summaries and regression coefficients of the significant climate variables in the models.

Regression model	Adj. R ²	P-value	B precip	B insol	F precip	F insol	F PET	F days T>25°C	F days T>30°C	V SAT	V precip	V insol	V days T>25°C	V days T>30°C
Floraison date	0.28	0.0009	0.075	-0.030										
Veraison date	0.38	<0.0001	0.038					-0.76						
Harvest date	0.54	<0.0001			-0.027			-0.84						-0.82
AOC red production	0.22	.0038	-2926								-2304			
Cab. Sauv. acid	0.66	<0.0001			0.012			-0.05						
Cab. Sauv. sugar	0.68	<0.0001			-0.066	0.049		0.92		-0.085				
Cab. Sauv. berry wts	0.67	<0.0001										0.143		1.58
Merlot acid	0.77	<0.0001					-0.05						-0.08	
Merlot sugar	0.79	<0.0001			-0.082	0.035		0.99		0.04	-0.141			
Merlot berry wt	0.59	<0.0001										0.140		2.46
Quality	0.62	<0.0001		0.011				0.17		-0.013				0.13

B, F, or V indicates that the parameter occurs during the budburst, floraison or veraison interval, respectively. Climate variables are as given in the text and only those variables that are significant are listed. A blank cell indicates that the variable does not significantly contribute to the regression model.

veraison generally resulted in a one day early or delayed harvest [4]). The exception to these relationships was between budburst and the other phenological events. The lack of inter-phenological correlation with budburst might indicate that temperature extremes had little impact on early season growth or that once budburst commenced, late periods of cold weather ultimately influenced the remaining phenological timing of the plants. It is also likely that the procedure used to determine budburst did not adequately estimate when the event actually occurred.

The phenological-interval climate influences on the timing of individual events showed that similar parameters influenced floraison, veraison, and harvest (Table 3). The timing of floraison was influenced by precipitation and hours of insolation during the budburst to flowering interval, with 28% of the variability in the timing of floraison described (Table 3). Precipitation levels showed a positive relationship indicating that too much rainfall delayed flowering. Hours of insolation were negatively related to floraison date, suggesting that increased sunshine promoted photosynthetic assimilation and inflorescence differentiation and limited “*coulture climatique*” (a French term for a climate-induced imbalance in vine tissue carbohydrates that results in poor fruit set) during this interval.

The date of veraison regression model described 38% of the variability in the timing of the event (Table 3). Increased amounts of precipitation during the budburst interval acted to delay veraison. Furthermore, as the number of days with temperatures greater than 30°C increased during the floraison interval, veraison occurred earlier. Given that budburst precipitation influenced the timing of floraison, it is clear that knowledge of earlier phenological occurrences provides insight into the timing of later growth events. By removing budburst precipitation and adding floraison date, 88% of the variation in veraison was explained by the date of flowering and the number of days with temperatures greater than 30°C during the floraison interval (not shown).

Both increased insolation and more days with temperatures greater than 30°C during floraison and veraison advanced harvest (Table 3). The model describes 54% of the variation in the timing of harvest, but as with the veraison model, knowledge of the timing of veraison described much more of the variability in harvest dates than any suite of climate variables in the interval ($R^2 = 0.75$, not shown). Of particular note is that the timing of harvest was not related to natural water deficits, although effects on other events were seen from water deficiencies just prior to the event (floraison), or earlier in the season (veraison) [26].

For the number of days between events, regression models were confounded by the use of two variables that are inevitably linked with elapsed time—SAT and PET. Both of these variables appeared as significant predictors of interval length but since they are based on accumulations, there is an inherent positive correlation between their relative values and interval length.

Model explained variance was very high (>97%) and regression coefficients were positive in each model. This highlights the weakness of using accumulated values of heat or temperature to predict or describe phenological events. The results are comparable to other studies [e.g., 4,8,13,15] and indicate that accumulations may only be applicable for interregional and global comparisons of potential grape growth and maturation [16]. Additionally, heat summations appeared in only one of the viticulture regression models (Merlot sugar, with a small but significant effect) lending further evidence that heat summations are not a useful climate parameter in viticulture research, at least in Bordeaux.

Production: AOC red wine production in the Bordeaux region has averaged just over two million hectoliters per year but has increased substantially in the 1990s, with vintages averaging nearly five million hectoliters per year [5] (Table 1). AOC red wine production increased nonlinearly from 1938 to 1997 (Fig. 3) due to improvements in technology and increases in acreage [33]. The most appropriate estimator of the production trend is a second order polynomial function (Fig. 3) and after detrending, the resulting deviations (residuals) about the trend were used as the dependent variable in subsequent analyses.

Timing of each of the floraison, veraison, and harvest dates displayed negative correlations with detrended AOC red wine production and revealed that production, like quality, decreased with delayed events (Table 2). Additionally, longer growing seasons (budburst to harvest) generally resulted in lower production ($r = -0.38$, not shown) and may be a result of less than ideal conditions in which growers leave the crop hanging longer to achieve optimum crop loads and composition. Overall, the volume of production played

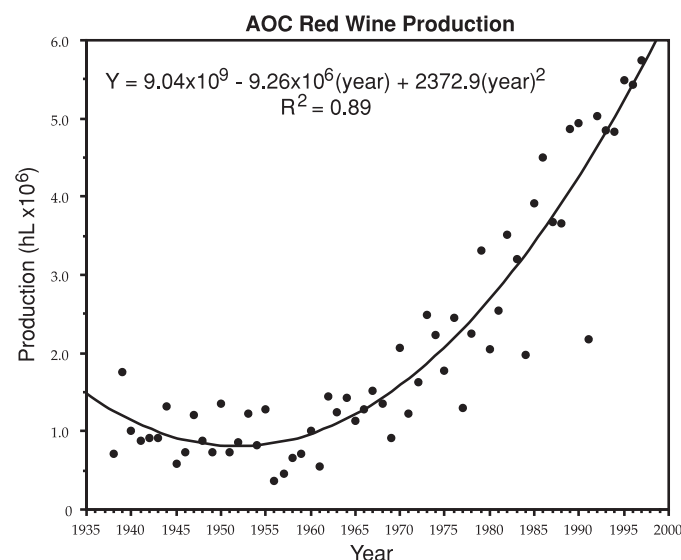


Fig. 3. Region-wide Appellation d'Origine Contrôlée red wine production for Bordeaux, 1938-1997. The second order polynomial equation used to detrend the series is given along with the trend line equation [32,43; data source, 6].

a small, positive role in vintage quality, although many years with high production had both high and low vintage ratings ($r = 0.31$, Table 2 and Fig. 4a). Furthermore, production levels had little effect on average composition (Table 2).

The climate characteristics during the growing season that influenced wine production was the relative amount of precipitation during the budburst and veraison intervals (Table 3). The signs of the regression coefficients are both negative indicating that rainfall, and the associated adverse weather leading up to flowering, can produce “*coulure climatique*” (i.e., affecting inflorescence differentiation and berry set) and that rainfall during veraison may aggravate moisture-related problems and increase the need for cluster and/or berry selection during harvest [26,35]. The model de-

scribes 22% of the variation in AOC red wine production and indicates that, while climate plays a role in crop production, other factors such as husbandry practices (i.e., ideal crop loads and fruit thinning) are probably more important in determining final production levels.

Composition: Compositional parameters of acid and sugar levels, along with berry weights just prior to harvest, give an overall indication of potential wine quality (Table 1). Cabernet Sauvignon total acid and sugar levels have averaged 5.2 and 190 g/L, respectively, while Merlot levels have averaged 4.6 and 203 g/L, respectively. Cabernet Sauvignon average total acid levels were always greater than or equal to those of Merlot, while average sugar levels were generally higher for Merlot (not shown). Sugar and acid levels were negatively correlated both within and between varieties with years of higher than average sugar having lower than average acidity (Table 2). Over the last 26 years, acid levels for both varieties displayed significant downward trends (Fig. 5a, 5b, respectively), while sugar levels for both varieties had no trend (Fig. 5c, 5d, respectively). The ratio of sugar to acid levels, a commonly-used measure of crop ripeness and quality [31,42], increased significantly over time for both varieties, indicating better overall vintages (not shown, $R^2 = 0.15$ for Cabernet Sauvignon and $R^2 = 0.23$ for Merlot).

Merlot 100-berry weights at harvest averaged 147 g with a standard deviation of 17.6 g (Table 1). Cabernet Sauvignon 100-berry weights averaged $120 \text{ g} \pm 13.1 \text{ g}$. Merlot had consistently higher berry weights for the reference vineyards (not shown). Berry weights at harvest for Cabernet Sauvignon and Merlot varieties have increased nearly 25% and 45%, respectively, during the time period (Fig. 5e, 5f, respectively). Both of these large increases are thought primarily to be a function of improved growing conditions during the 1980s and 1990s, although some of the increase could be attributed to improved husbandry, the use of different clones, less diseased rootstock, etc. No significant relationship was observed between berry weights and acid or sugar levels for either variety (Table 2).

The three composition parameters each exhibited significant relationships with grapevine phenology. Acid levels for both varieties showed large positive correlations with floraison, veraison, and harvest dates indicating that delayed phenology means higher relative acidity (Table 2). Sugar levels and berry weights, on the other hand, displayed large negative correlations indicating that earlier phenological timing produced a riper and larger crop. Combined, these relationships reveal that earlier than average events in the growth stages foretell of higher sugar to acid ratios, a larger crop, and a better vintage.

For compositional parameters, 66% of the variability in Cabernet Sauvignon acid levels was explained by rainfall during floraison (positive effect), while more days with temperatures greater than 30°C during

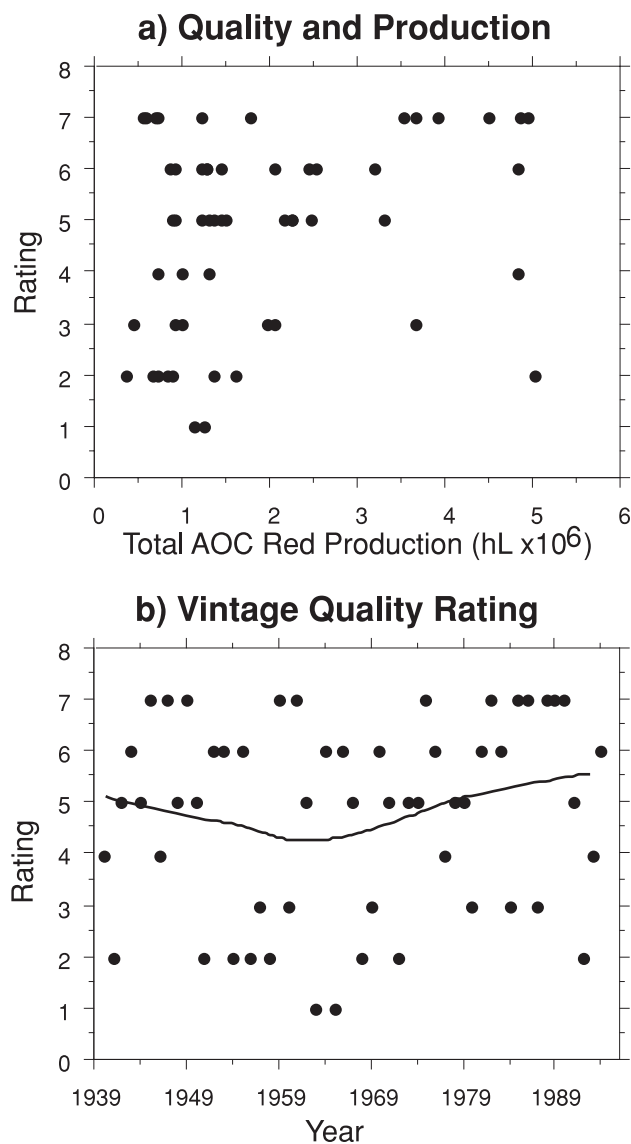


Fig. 4. Comparisons between production and vintage quality for Bordeaux: (a) scatterplot of the relationship between vintage quality and production ($r = 0.31$). (b) time series of the rating given each vintage from 1940-1994 with a LOWESS curve superimposed on the record.

floraison and veraison lowered total acidity (Table 3). Seventy-seven percent of the variability in Merlot acid levels was explained by floraison interval PET and the relative number of days with temperatures greater than 25°C during veraison (warm and dry conditions decrease acidity) (Table 3).

Regression models for sugar levels displayed opposite relationships compared to those found for the acid levels. For Cabernet Sauvignon, four climate variables collectively explain 68% of the variability in sugar levels (Table 3). Floraison and veraison interval precipitation had a negative impact on sugar levels [26,35], and the relative amount of insolation during flowering and days with temperatures greater than 30°C produced a positive effect. For Merlot, 79% of the harvest sugar levels were explained with the same floraison and veraison interval precipitation and floraison insolation variables as found in the Cabernet Sauvignon model (Table 3). Merlot sugar levels were, however, more influenced by the relative number of days with temperatures greater than 25°C (Cabernet Sauvignon has the number of days > 30°C) and the inclusion of the veraison interval SAT, which had a positive coefficient (Table 3).

For Merlot and Cabernet Sauvignon, 59% and 67% of the variability in berry weights, respectively, were described by the relative amount of insolation and the number of days with temperatures greater than 30°C during the veraison interval (Table 3). The climate influences during this interval showed that high levels of insolation, along with overall warm conditions, promote growth of the berries.

Variations in Merlot acid and sugar levels were more readily described by phenological-interval climate variability than Cabernet Sauvignon, while berry weights were the opposite (Table 3). Additionally, Merlot sugar and acid levels were significantly related to the relative number of days with high temperatures (greater than 25°C), while Cabernet Sauvignon sugar and acid levels appeared to be more influenced by higher temperatures (days greater than 30°C). This observation gives an indication that Merlot composition is more climatically sensitive than is Cabernet Sauvignon.

Quality: For the time period, there has been considerable year to year variability in vintage quality with many more years given exceptional ratings [12] than poor ratings (2) (Table 1, Fig. 4b). Superimposed on Figure 4b is a smoothed line using LOcally WEighted regreSSion (LOWESS) that helps identify the underlying pattern. Vintage quality generally declined from 1940 through the mid-1960s and increased from the mid-1960s through 1995.

With the exception of budburst, vintage quality was negatively related to each phenological event, meaning that early phenological events tended to produce the best vintages (Table 2). While only the harvest date exhibited a significant trend toward earlier occurrences over the period of record, each of the time series,

from the late 1970s and early 1980s, has shown a tendency to occur earlier. This period of generally earlier phenology was largely responsible for the greater number of good vintages Bordeaux has experienced in the last two decades (though some obvious exceptions can be found).

Both acid and sugar variations were significantly related to vintage quality in a negative and positive manner, respectively (Table 2). While this does not mean that all acid levels are detrimental, it does indicate that fully ripe grapes at harvest, possessing high sugar levels, tend to raise vintage quality. Berry weights, for both varieties, were not significantly related to vintage quality for the time period (Table 2).

Given the strong influence compositional parameters had on vintage quality [4,15], regression models were examined for the effect sugar and acid levels had on vintage quality. Multi-collinearity between acid and sugar levels, and between varieties, confounded the regressions; therefore, a sugar to acid ratio was used as independent variables in the models. While both Merlot and Cabernet Sauvignon sugar/acid ratios resulted in significant models, the Cabernet Sauvignon ratio described 78% of the vintage rating compared to 61% for the Merlot ratio (not shown). This result hinted that, although both varieties are important in Bordeaux, variations in Cabernet Sauvignon are more influential in determining overall vintage quality. Additionally, Jones and Storchmann [20], in an econometric analysis on Bordeaux wine market prices, found that, in climatically good years, both Merlot- and Cabernet Sauvignon-dominated wines achieved equally high vintage ratings and prices paid at auction. In vintages in which the climate was more marginal, châteaux that have a high percentage of Merlot in their blend achieved below average ratings and prices at auction. Furthermore, knowing the climate in a given year often gives a better prediction of subscription prices (futures) than the dependence on the ratings of a few individuals [20].

Climate influenced vintage quality over the entire growing season. Four climate variables described 62% of the variability in vintage rating (Table 3). Insolation levels during the budburst interval had a positive effect, presumably by initiating high levels of photosynthetic activity. An increased number of days during floraison and veraison with temperatures greater than 30°C were positively related to quality by influencing early growth events and complete maturation [4]. Additionally, rainfall during veraison decreased quality through berry dilution and/or moisture-related problems [26,35]. Interestingly, harvest date alone accounted for 42% of the variance in vintage ratings (*i.e.*, early harvest equals better vintages, not shown). These results are similar to a classification of the quality of the vintages by Desclee [11], which used fixed 10-day intervals to assess the climatic influence on quality. Using the same reference vineyard data (1953-1984) and a combination of principal components, cluster, and discriminant analyses, Desclee identified that

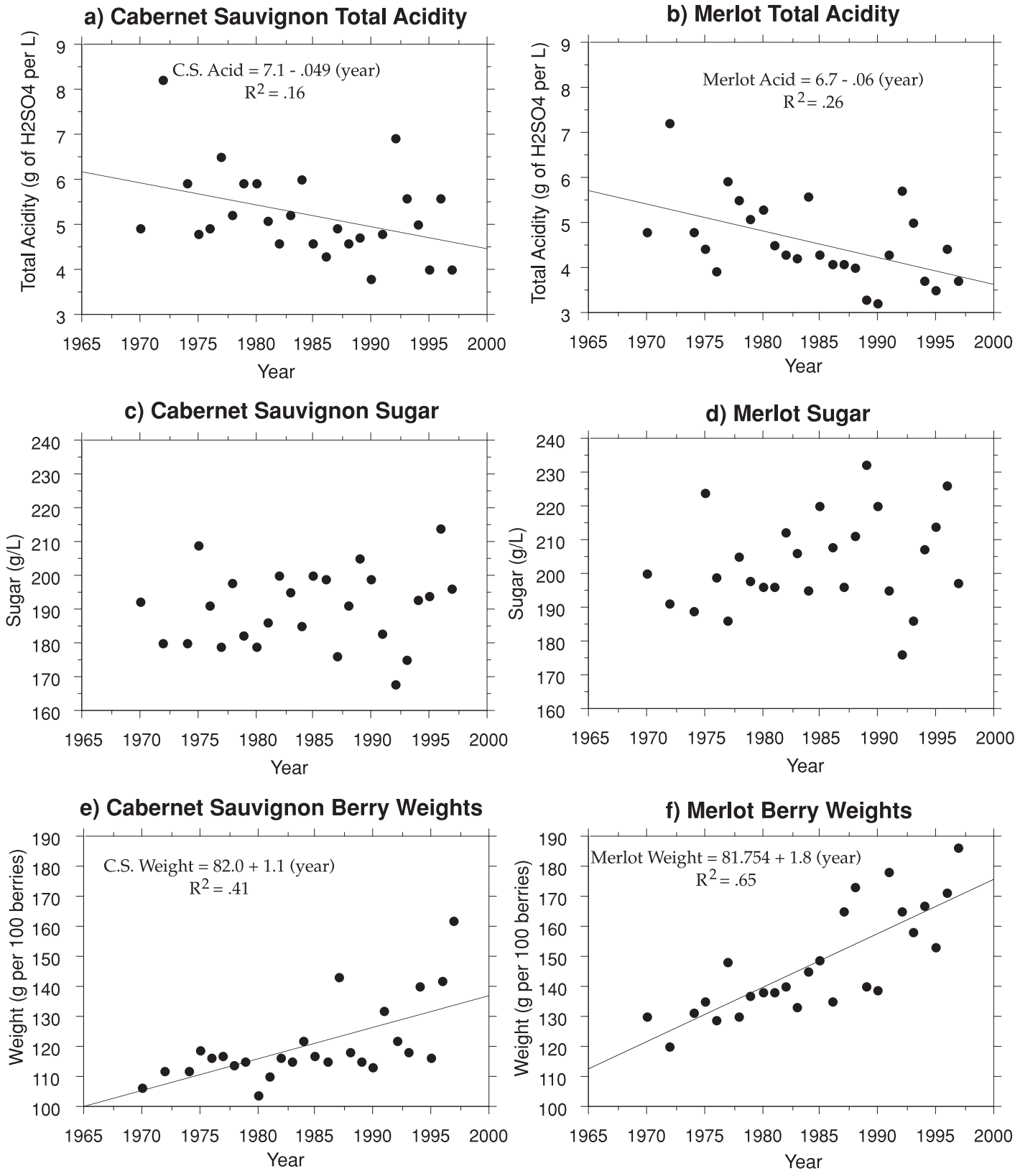
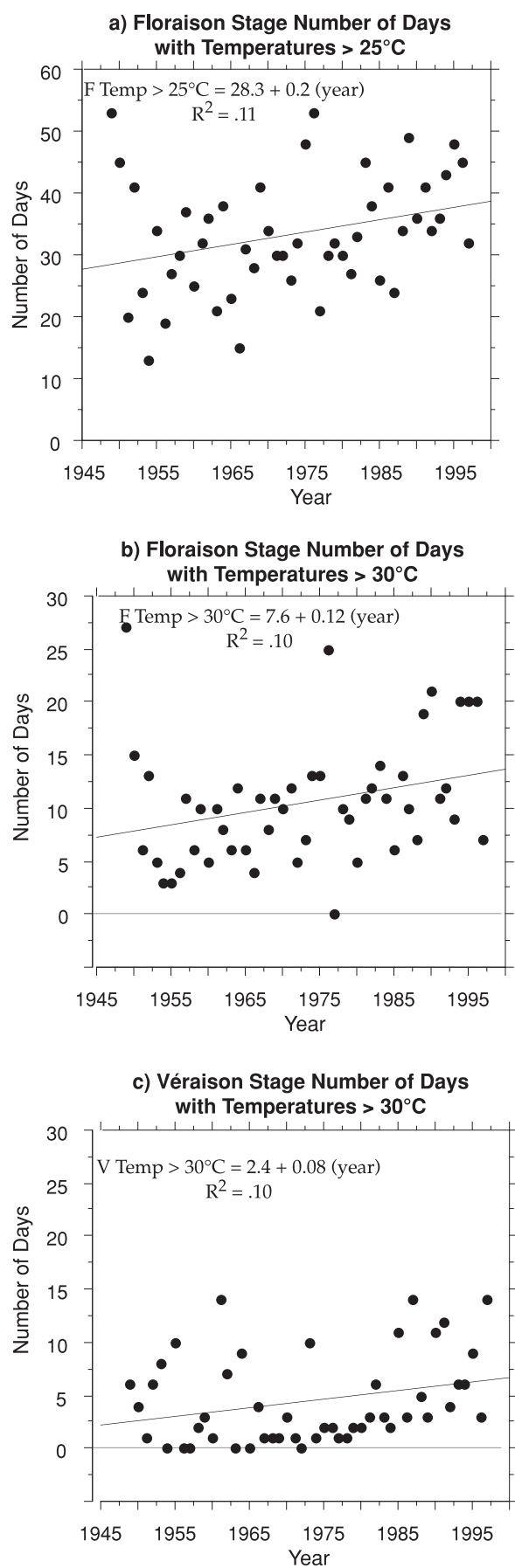


Fig. 5. Time series of Bordeaux reference vineyard composition parameters for (a) Cabernet Sauvignon total acidity, (b) Merlot total acidity, (c) Cabernet Sauvignon sugar, d) Merlot sugar, (e) Cabernet Sauvignon berry weights, and (f) Merlot berry weights. Only significant trends are shown and they are described by the inset equations.



maximum temperatures, insolation, and rainfall during 10-day intervals near floraison, veraison, and harvest helped to differentiate the quality of the vintages.

Trends in climate: Given the significance of the relationships between phenological-interval climate and viticulture parameters, an examination of the trends in individual climate variables may provide insight into future grape growth, production, and wine quality in Bordeaux. Of the 27 possible climate variables used in this study, only five exhibited any significant trend over the time period (dormant interval PET increased, dormant interval number of days less than -2.5°C decreased, and floraison interval variables of days over 25°C and 30°C , and veraison interval days over 30°C increased). Of those, three during the growing season also had significant influences on grapevine phenology, grape composition, and quality (Fig. 6). During the floraison interval, the relative number of days with temperatures greater than 25°C or 30°C increased nearly 10 and six days for the time period, respectively (Fig. 6a and 6b). During the veraison interval, the number of days with temperatures greater than 30°C increased by four days (Fig. 6c). These three variables appeared in many of the regression models, indicating that their increased occurrence was largely driving the climatic component of earlier phenology, greater sugar and lower acid levels, and increased vintage quality (Table 3).

While none of the dormant interval climate variables appeared as significant variables in the regression models, two exhibited significant trends over time. The dormant interval PET, or the difference between the SAT and precipitation, increased substantially, meaning that winters have become warmer and drier for the time period (not shown). A further indication of this dormant period warming was that the relative number of days with temperatures below -2.5°C has declined by 12 days from the early 1950s through the late 1990s (not shown).

In addition, in a comprehensive daily synoptic climatology, Jones [19], Jones and Davis [21] and Jones and Davis [in preparation], have found that the relative frequency of a small number of atmospheric circulation patterns over the North Atlantic and Western Europe and air masses, as identified for Bordeaux, largely drive the local climate and play significant roles in grapevine growth, production, and quality. From these detailed studies, trends in the occurrence of phenological-interval air masses indicate that milder conditions during critical growth stages has occurred, increasing the likelihood that the run of good vintages in Bordeaux will continue.

Conclusions

Overall, the phenology of grapevines in Bordeaux has shown a tendency toward earlier events in the last two decades, a shortening of growth intervals, and a lengthening of the growing season. Trends in grape composition at harvest, for the Merlot and Cabernet Sauvignon varieties, indicate a higher sugar to total acid ratio (mostly driven by

Fig. 6. Trends of the statistically significant phenological-interval climate parameters appearing in the regression models. See Table 3 for each variable's relationship to the viticulture variables. The regression equation and explained variance are inset on each chart.

decreasing harvest acid levels) and greater potential quality. Acid levels are much more influenced by phenological timing than sugar levels, indicating that years in which the events are delayed are years in which acid and sugar levels at harvest are increased and decreased, respectively. The correlations between climate and composition are typically higher for Merlot than for Cabernet Sauvignon and could be an indication that Merlot is more phenologically and climatologically sensitive. Vintage ratings have shown a general increase over the last two decades that is concomitant with the observed phenology and composition trends. While it is clear that climate plays a large role in wine quality; knowledge of phenological timing describes nearly half the variability in ratings with early events and shorter growth intervals resulting in better vintages. Additionally, sugar to acid ratios reveal that both Merlot and Cabernet Sauvignon influence Bordeaux wine quality, although Cabernet Sauvignon describes substantially more of the variability in ratings. This indicates that the wine industry in Bordeaux is more dependent on good vintages from Cabernet Sauvignon than from Merlot.

In conclusion, unique combinations of weather elements act to influence the phenology, quantity, and quality of Bordeaux vintages. The division of the growing season into physiologically correct stages, as dictated by the grapevines, gives more insight into the crop/climate relationship than calendar date divisions by revealing when, during the major growth intervals of the grapevines, certain climate elements act to influence grape growth and production. Of particular note is that fact that heat summations lack significance in relationships to vine physiology, production, and quality in Bordeaux [8]. This reveals that heat summations have limited use in viticulture studies and may only be applicable for interregional and global comparisons of potential grape growth and maturation. The results obtained in this study also highlight the need for more long term and consistent monitoring of grapevine growth stages at the vineyard, appellation, and region levels. Without such data, viticulturists do not have the tools necessary to understand historical and future viticulture trends. Ultimately, the lack of good data leaves researchers confined to modeling phenology in order to study the effects that climate and plant variability have on the crop's ability to produce and its relationship to the economy of a region.

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