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ORIGINAL PAPER

Partitioning the grapevine growing season in the Douro Valley of Portugal: accumulated heat better than calendar dates

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Abstract Temperature and water status profiles during the growing season are the most important factors influencing the ripening of wine grapes. To model weather influences on the quality and productivity of the vintages, it is necessary to partition the growing season into smaller growth intervals in which weather variables are evaluated. A significant part of past and ongoing research on the relationships between weather and wine quality uses calendar-defined intervals to partition the growing season. The phenology of grapevines is not determined by calendar dates but by several factors such as accumulated heat. To examine the accuracy of different approaches, this work analyzed the difference in average temperature and accumulated precipitation using growth intervals with boundaries defined by means of estimated historical phenological dates and intervals defined by means of accumulated heat or average calendar dates of the Douro Valley of Portugal. The results show that in situations where there is an absence of historical phenological dates and/or no available data that makes the estimation of those dates possible, it is more accurate to use grapevine heat requirements than calendar dates to define growth interval boundaries. Additionally, we analyzed the ability of the length of growth intervals with boundaries based on grapevine heat requirements to differentiate the best from the worst vintage years with the results showing that vintage quality is strongly related to the phenological events. Finally, we analyzed the variability of growth interval lengths in the Douro Valley during 1980–2009 with the results showing a tendency for earlier grapevine physiology.

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Introduction

Quality wines are produced in distinct regions with different climates, with the majority located between approximately 30° and 50° latitude, in both the Northern and the Southern Hemispheres. The baseline climate characteristics of a region determine the type of grapes that can be grown and the types of wines that can be produced, while weather variability influences the ripening of wine grapes, which in turn affect the variability of vintage-to-vintage productivity and quality (Jones et al. 2012).

The Douro Valley wine-producing region is situated inland in the northern portion of Portugal (Fig. 1) and is well known for the production of Port wine, long considered one of the best wines in the world. The region also produces dry red and white wines from traditional varieties grown in the region. Previous research has shown that the overall production and quality of the vintages in the Douro Valley varies due to weather and climate variability (Santos & Malheiro, 2011; Jones & Alves, 2012). Understanding the linkages between weather and/or climate variability and vintage quality/yield variability has become an important scientific and economic research subject. Primault (1969), Winkler et al. (1974), Bindi et al. (1996), Jones and Davis (2000), Grifoni et al. (2006), Lopes et al. (2008), Ashenfelter (2008), Mattis (2011), Gladstones (2011), Parker et al. (2011), and numerous other researchers have conducted research on modeling the relationships between weather and climate variability and grapevine annual yield and/or fruit/wine quality. Results from these

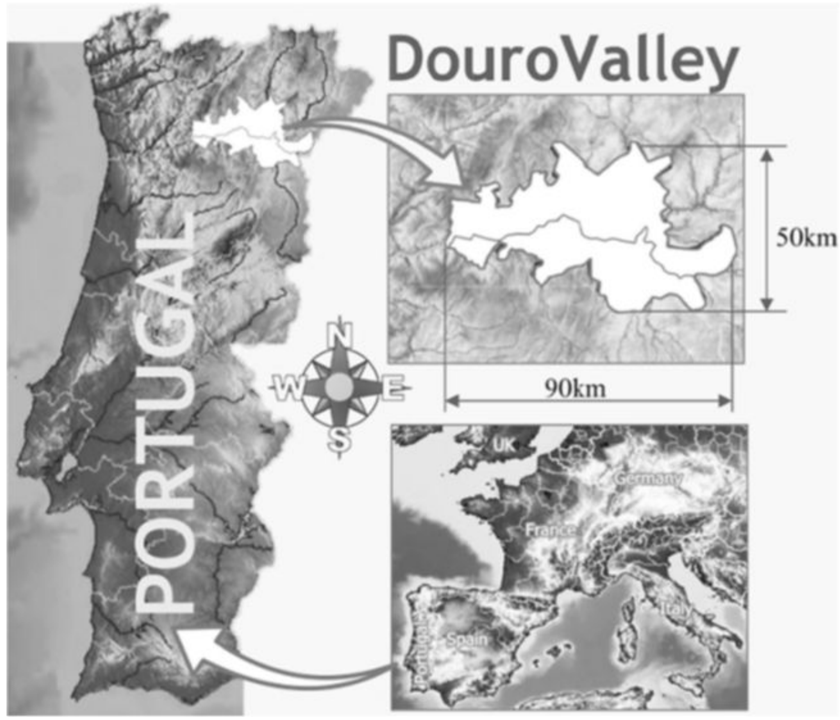


Fig. 1 Portugal and Douro Valley location

studies show that grapevine phenological timing and length of time between events is strongly tied to temperature-based measures such as degree-days and other bioclimatic indices. Still others have used the strong relationships between climate, vine growth, production, and quality to examine climate change impacts (Jones et al. 2005; Duchêne & Schneider 2005; Webb et al. 2007; Schultz & Jones 2010; Tomasi et al. 2011). The results show that grapevine phenology has generally trended earlier (approximately 5–10 days per 1 °C of warming), with shorter interphases between events (shortening of 10–20 days), both of which has been related to higher sugar content, lower acidity, and changes in vintage ratings.

The development cycle of the grapevine is usually divided into three major phases: inflorescence development, berry development, and ripening. These three phases are bounded by the phenological events that determine the beginning/ending of each phase (Jones 2013): budburst, flowering, *véraison*, and maturity. The most common means to determine the dates of each phenological event are based on observations of grapevines using the guidance of a growth descriptive system. Several descriptive systems have been used to identify grapevine growth stages: Baggiolini (1952), Eichhorn and Lorenz (1977), and the modified BBCH scale for grapevines (Lorenz et al., 1994). Descriptive systems provide a sequence of distinctive grapevine development stages clearly recognized, described in an unambiguous and widely understood language that allow the identification of each stage (Coombe 1995).

While there are some long-term observations of grapevine phenology in various places worldwide (Jones 2013), in many regions, data is often only collected for one event (e.g., maturity) or likely only for a few years. This is the case for the Douro Valley in that there are no readily available consistent records of the dates of any of the main phenological events for an extended period. In cases such as this where grapevine phenological event data are not available or limited, researchers often use calendar-defined periods to partition the growing season and to examine weather and/or climate influences (e.g., Corsi & Ashenfelter 2001; Grifoni et al. 2006; Makra et al. 2009; Mattis 2011). Some studies partition the grapevine growing season into smaller intervals using calendar-defined weeks or months (e.g., from week x to week y or from March to June). Other studies partition the season into intervals whose bounds are defined using a calendar simplification of plant phenology, making use of accepted dates when, on average, the main phenological events happen in a region (e.g., budburst by the end of March, flowering by the beginning of June, *véraison* by the end of July, and maturity by mid-September). While this method may provide some insight into the relationships between climate, vine growth, production, and quality, it would be arguably better to base the division on plant responses to the weather in a given vintage.

Previous research has shown that measures of accumulated heat help describe grapevine growth in numerous settings and across many varieties (e.g., Lopes et al. 2008; van Leeuwen et al. 2008; Parker et al. 2011; Gladstones 2011 and others). These studies use a thermal time model, based on the observation that each phenological event occurs when a critical amount of accumulated heat above a critical threshold temperature is reached (Bonhomme 2000). While it is generally accepted that 10 °C is the threshold temperature (Winkler et al. 1974; Huglin 1978; Carbonneau et al. 1992), others have found that this threshold varies by variety, location, the period of vine growth, and the water status of the plants in the season of interest (Jones 2013). To consider dormant period influences, some models incorporate the effect of chilling temperatures during the winter on the breaking of buds in the spring (Chuine, 2000; Cesaraccio et al. 2004; Fila et al. 2012; and others). However, good agreement between phenology dates, estimated using the thermal time model, and the historical average phenology dates in the Douro Valley, as well as the simplicity of the model, justify the choice of this model for this research.

Jones and Davis (2000) suggested the use of grapevine phenological events to define growth periods as they give more insight into the crop/climate relationship than the calendar date divisions. Growth interval boundaries defined using fixed calendar dates are expected to have weak agreement with growth interval boundaries defined using the observed dates. Salazar-Gutierrez et al. (2013) consider that heat accumulated over time provides a more accurate physiological estimate than counting calendar days. We note that using the region heat summation to define the phenological intervals has been criticized for not taking into account site-to-site variability that may depend not only on temperature but also on the grape variety, soils, site orientation, and water uptake conditions (van Leeuwen et al. 2008) and that, in some cases, heat summations may lack significance in the relation to vine physiology (Jones and Davis 2000). However, since detailed records on grapevine physiology are not available in general, the use of heat summation to define when each phenological event occurs should be considered a good approximation to define the growth intervals.

The purpose of this research was to analyze temperature and precipitation characteristics and differences using growth intervals with boundaries defined by the estimates of historical dates of the main phenological events (used as reference) and growth intervals with boundaries defined by two methods: method 1—by mean values of the heat requirements of the main phenological events and method, and method 2—by generalized calendar average dates associated with the occurrence of the main phenological events. Additionally, in order to illustrate the importance of accurately defining the growing intervals, this research analyzed the ability of the length of growth intervals with boundaries based on grapevine heat requirements to differentiate the best from the worst vintage years. Finally, the variability and trends of phenology dates and of growth interval lengths in the Douro Valley during 1980–2009 was analyzed.

Data and methods

This section describes the datasets used to characterize the weather/climate and vintage quality as well as the methods used to divide the growing season into four smaller growth intervals bounded by January 1 and by the main phenological events of budburst, flowering, *véraison*, and maturity. In addition, the method used to differentiate the best from the worst vintage years is briefly described.

Weather data

To characterize the weather in the Douro Valley, a dataset of daily maximum and minimum temperatures (°C) and precipitation (mm) for the period 1980–2009 was collected from five local meteorological stations belonging to the Portuguese National Meteorological Service (IM): *Carrazeda de Ansiães, Mirandela, Pinhão, Régua,* and *Vila Real* (Fig. 2). The data collected from these weather stations was not

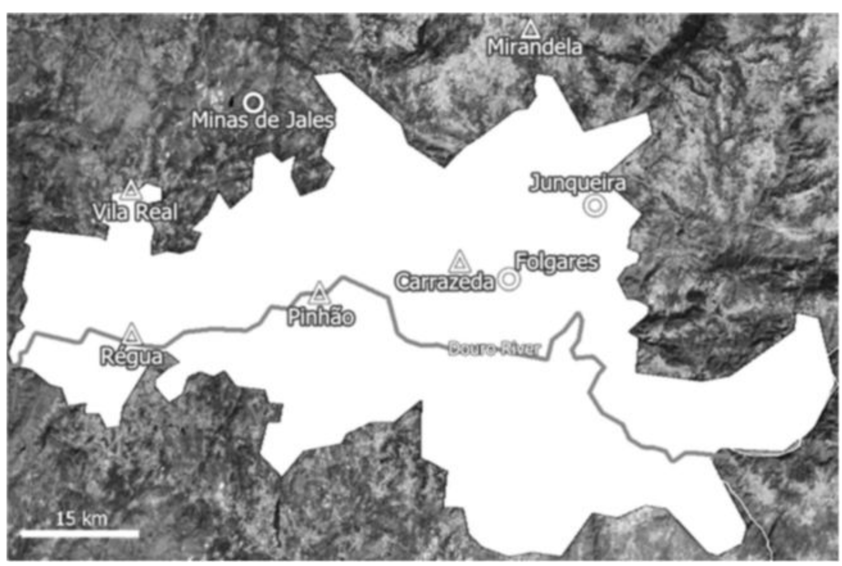


Fig. 2 Location of the local weather stations. IM weather station (*circular icons*) and SNIRH weather station (*triangular icons*)

complete and included some missing values that varied from a minimum of 0.0 % in *Vila Real* to 17.4 % in *Carrazeda de Ansiães* for precipitation and a minimum of 0.0 % in *Vila Real* to 10.6 % in *Carrazeda de Ansiães* for temperature. In addition, the dataset was supplemented with data collected from three local meteorological stations belonging to the National Information System for Water Resources (SNIRH—*Sistema Nacional de Informação de Recursos Hídricos*). The stations are *Folgares, Junqueira,* and *Minas de Jales* (Fig. 2). Reference series for each weather variable and for each time period were created for each candidate station using the better-correlated neighbor weather stations for that particular variable. The reference series variable's values were calculated using a weighted average of the linear regression values for the same variable for the selected neighbor stations. Values from the reference series, for each variable, were used to fill the candidate station missing values for that variable.

All meteorological data series used in this research were examined and cleaned of erroneous values using the methodology proposed by Feng et al. (2004) and homogenized by using a software package for data homogenization—RHtestsV3 (Wang 2011). Mean temperature data series were obtained by averaging maximum and minimum temperatures. Grapevine heat requirements to reach each key phenological stage were defined in growing degree-days (GDD)—the sum of the average daily temperature above a threshold temperature from January 1 to a given date: GDD (°C)=$\sum_{i=1\ (\text{January } 1)}^{\text{O. Date}}(T_{avg}-T_{base})$, where T_{avg} is the average temperature in °C and T_{base} is a temperature used as threshold. While a threshold temperature of 3.5 °C has been used for budburst (Lopes et al. 2008), 10 °C is the most commonly used base temperature in viticulture (van Leeuwen et al. 2008; Jones et al. 2010) and was used for all events in this research.

Vintage consensus ranking for Port wine 1980–2009

In order to select the best and the worst vintages for Port wine in the 1980–2009 period, the consensus ranking method proposed in Borges et al. (2012) was used. The method makes use of a rank aggregation algorithm to combine a collection of vintage charts for the Douro Valley with a ranking of the vintages that represents the consensus of the input vintage charts. As a result, an impartial ranking of the vintages that represents the consensus of the set of independent vintage charts was obtained. The consensus ranking for Port wine vintages during 1980–2009 was obtained using this method and is shown in Table 1. This ranking represents an impartial consensus of the collection of input vintage charts, in the sense that no assumption is made on how each vintage chart was formulated. The consensus ranking was used as a relative measure of vintage quality.

Grapevine phenological data

In this section, the approach used to estimate the yearly dates of the main phenological events from the historical average dates and the two methods used to divide the growing season into smaller intervals are described.

Observations: characterizing the main phenological events from estimates of historical dates

Data covering the phenology of grapevine for the entire region over a long time period is not available for the Douro Valley. However, the research was able to obtain the average observed dates of the main events for the city of *Régua* (Fig. 2) from ADVID—*Associação para o Desenvolvimento da Viticultura Duriense* (ADVID 2012), which are shown in Table 2 (no information is given on the number of years used in the averages nor on the phenological scale used). In addition, this research also used the observed dates of the main events for the *Touriga Franca* variety, in 2001–2012, at *Quinta de Santa Bárbara* (QSB), located in *Pinhão* (Fig. 2), and the values are also presented in Table 2.

The values show that the average dates are quite similar for budburst, bloom, and maturity, yet there is a difference of 14 days for *véraison*. However, since the ADVID records are referenced to a larger area and represent an average value that incorporates several grape varieties, as opposed to the QSB data that is for a single grape variety, the ADVID data was used as the reference values for the main phenological events in the Douro Valley in this research. To produce yearly dates of the main phenological events for the region, the average accumulated heat (GDD) needed to reach each event was used. ADVID average phenological dates correspond to the following average accumulated heat: budburst—75 GDD, flowering—385 GDD, *véraison*—929 GDD, and maturity—1697 GDD.

Method 1—characterizing the main phenological events from experimental heat requirements of representative grape varieties

Lopes et al. (2008) and van Leeuwen et al. (2008) studied the heat requirements for several grape varieties. While the van Leeuwen et al. (2008) study covered the most widely planted

Table 1 Vintage quality consensus ranking for Port wine in 1980–2009

Vintage	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09
Rank	15	30	17	7	27	8	26	18	28	14	25	9	10	29	1	13	24	6	20	23	3	19	22	4	12	11	21	2	16	5

Table 2 The average dates of the main phenological events obtained from ADVID and from QSB

Event	ADVID		QSB	
	Average ordinal date	Calendar date	Average ordinal date	Calendar date
Budburst	75	March 16	83	March 24
Flowering	140	May 20	143	May 24
Véraison	191	July 10	205	July 25
Maturity	247	September 4	246	September 3

varieties in the world collected throughout Europe, the Lopes et al. (2008) study focused on 34 varieties of the Portuguese Ampelographic Collection that includes the main wine grape varieties grown in the Douro Valley (Table 3). The van Leeuwen et al. (2008) study collected data from a wide range of cultivars in many wine growing regions (i.e., mostly in Europe, over many vintages). For bud break, GDD were calculated when 50 % of the buds reached Baggiolini's B stage (Baggiolini 1952). For flowering, GDD were calculated when 50 % of the flowers were open. For *véraison*, GDD were calculated when 50 % of the berries changed color (red varieties) or softened (white varieties). Harvest dates in regions where each specific variety is widely planted were treated as the dates of maturity for analysis. The Lopes et al. (2008) study collected data from *Quinta da Almoinha*, *Estação Vitivinícola Nacional*, just north of Lisbon (39° 02′ N and 9° 11′ W) during 1990–2006, observing phenology and climate protocols of the OIV (1983).

The only comparable grape variety in the two studies is *Tinta Roriz* (*Tempranillo*). The results show that the heat requirements to the budburst and flowering events are equivalent according to the two sources (budburst GDD=50 and flowering GDD=355). In addition, the heat requirements for the *véraison* event are very similar (1030 GDD vs 1027 GDD, $\Delta\approx0.3$ %). The value for maturity is not given in the van Leeuwen et al. (2008) study. The agreement of the two sources concerning the heat requirements for these three events suggests that, in general, the two sources are comparable. We note that the *Tinta Roriz* variety represents 12 % of the Douro Valley vineyards while the most planted variety, *Touriga Franca*, represents 22 % of the Douro Valley vineyards (Magalhães 2003; Copello 2010). Figure 3 shows the relative heat requirements for the six grape varieties most commonly grown in the region according to Lopes et al. (2008). The two main varieties are each indicated separately while the other four are not individually identified.

For defining the heat boundaries for growth intervals, analysis of Fig. 3 suggests that *Tinta Roriz* is the variety that best represents the Douro Valley's most planted varieties for the first three phenological events, but not so for maturity. *Tinta Roriz* is an early maturity variety that ripens much earlier than the average of the other varieties. In fact, Fig. 3 shows that the heat requirements to maturity of the *Touriga Franca* variety better represent the region since it is the most planted variety, and its heat requirement value is close to the average heat requirement of all six varieties for maturity (1608 GDD). Thus, we chose to use GDD=1626, the *Touriga Franca* value,

Table 3 Heat requirements for common grape varieties grown in the Douro Valley

			Heat requirement to reach each key phenological stage (GDD)											
Source	Phenological event	GDD T_{base}—threshold temperature (°C)	*Tinta Roriz* (*Tempranillo*)	Σ	*Tinta Barroca*	Σ	*Tinto Cão*	Σ	*Tinta Amarela* (*Trincadeira*)	Σ	*Touriga Franca*	Σ	*Touriga Nacional*	Σ
Lopes et al. (2008)	Budburst	3.5	582	582	544	544	545	545	614	614	528	528	552	552
	Budburst[a]	10.0	50	50	47	47	48	48	54	54	43	43	45	45
	Flowering	10.0	305	355	300	347	294	342	311	365	292	335	293	338
	Véraison	10.0	675	1030	620	967	771	1113	715	1080	618	953	778	1116
	Maturity	10.0	486	1516	617	1584	470	1583	559	1639	673	1626	535	1651
van Leeuwen et al. (2008)	Budburst	3.5												
	Budburst	10.0	50	50										
	Flowering	10.0	305	355										
	Véraison	10.0	722	1027										
	Maturity	10.0	–	–										

[a] T_{base}=10.0 °C, estimated from T_{base}=3.5 °C values

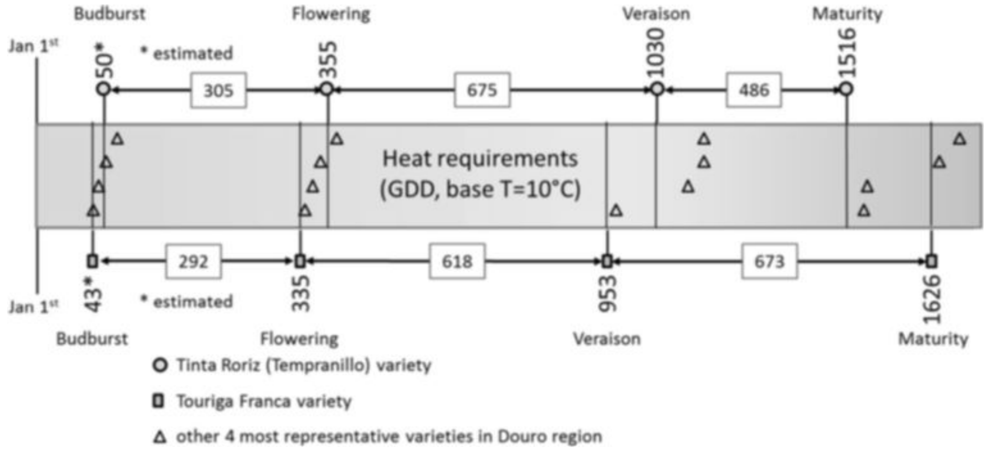


Fig. 3 Relative heat requirements for the six recommended varieties for Port wine

as the heat requirement for maturity in the region. In summary, the heat requirements used as representatives for all varieties in the Douro Valley are the following: budburst—50 GDD, flowering—355 GDD, *véraison*—1030 GDD, and maturity—1626 GDD.tgroup1

Method 2—characterizing the main phenological events from average calendar dates

When there are no historical phenological data available or reference heat requirement values for a region, a common approach is to consider the generally accepted average dates for the main phenological events. For example, it is generally accepted that in the Northern Hemisphere, the maturity event happens, on average, between the middle of September to the middle of October depending on region and variety. For simplicity, Northern Hemisphere average dates were used as a reference of the Douro Valley's boundary dates for the growth intervals (Jones 2013). Ordinal dates and the corresponding calendar dates for the main phenological events are presented in Table 4.

Summary of the two methods

This section presents a summary of the methods presented in the previous sections. Each vintage growing season was partitioned into four smaller growth intervals. The last three growth intervals are coincident with the three major phases of grapevine development. These intervals are based on the main phenological events and include (1) end of dormancy interval—the period from the beginning of January to budburst, (2) inflorescence development interval—the period from budburst to flowering, (3) berry development interval—the period from flowering to *véraison*, and (4) ripening interval—the period from *véraison* to maturity. A summary of growth interval boundaries according to each of the methods is given in Table 5.

Table 4 Generally accepted average dates for main phenological events in the Northern Hemisphere

Event	Average ordinal date	Calendar date
Budburst	91	April 1
Flowering	161	June 10
Véraison	206	July 25
Maturity	258	September 15

Relationships between vintage quality, phenological event dates, and growth interval lengths

The ability of growth intervals based on grapevine heat requirements to differentiate the best from the worst vintages was analyzed. The growing season was partitioned into four smaller growth intervals bounded by January 1, budburst, flowering, *véraison*, and maturity with the boundaries of each growth interval defined based on grapevine heat requirements. We first analyzed all series with the ordinal dates of the main phenological events and growth interval lengths for normality, using the Shapiro-Wilk test which is considered superior to the K-S test when samples are small, containing less than 50 elements (Razali and Wah, 2011), and for homoscedasticity, using the White test. Differences between the average dates of the main phenological events for the top n vintages and for the bottom n vintages were tested using t test.

Results and discussion

The results are presented and discussed from three different perspectives. First, values of weather variables (average temperature and accumulated precipitation) resulting from the use of the two methods for defining the growth interval boundaries are compared with the corresponding values obtained when using reference yearly historical dates. Then, the ability of

Table 5 Summary for growth interval boundaries based on GDD (method 1) and calendar dates (method 2). Reference historical dates are estimated from the average GDD needed to reach each date, each year

			Growth Interval				
			End of Dormancy	Inflorescence Development	Berry Development	Ripening	
Method	**Boundaries**	**Units**	**Jan 1**	**Budburst**	**Flowering**	***Véraison***	**Maturity**
Reference	Estimated yearly dates	GDD	0	75	385	929	1697
1	Cultivar heat requirements	GDD	0	50	355	1030	1626
2	Calendar dates	Date	1	91	161	206	258

phenology dates and growth interval lengths based on grapevine heat requirements to differentiate the best from the worst vintages is examined. Finally, the evolution of the grapevine phenology in the Douro Valley during 1980–2009 is analyzed.

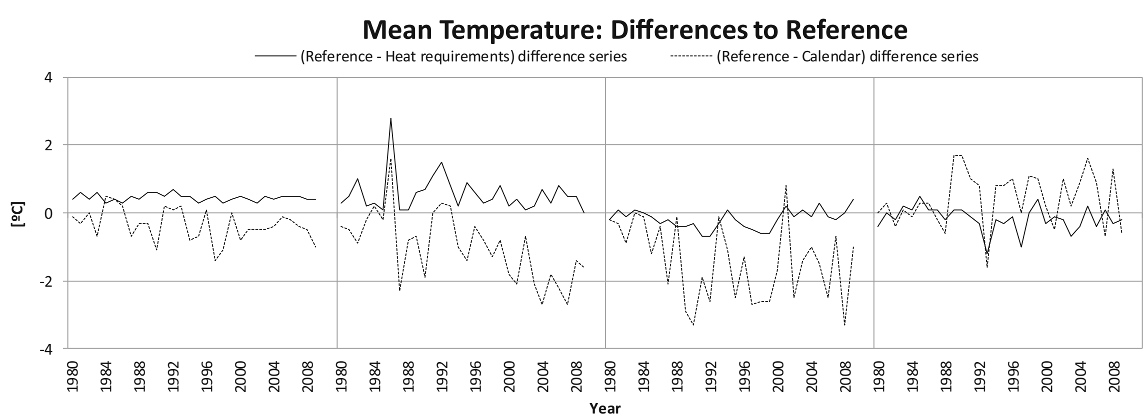
Comparing the methods used in the definition of growth intervals boundaries

For each year during 1980–2009, the growing season was partitioned into the four growth intervals (end of dormancy, inflorescence development, berry development, and ripening) using the previously described methods. For each growth interval, two weather variables commonly used in characterizing weather profiles—mean temperature and precipitation amount—were assessed. The values obtained from yearly historical data were used as reference values. The values obtained from the common varieties' experimental heat requirements (method 1) and the values obtained from average calendar dates (method 2) were compared to the corresponding reference values.

Figure 4 shows, for each growing interval and for a given year, the difference between the average temperature when the interval is defined from historical phenology data (reference) and when the interval is defined by each of the two alternative methods (method 1 and method 2). The results show that the differences in the mean temperatures are, on average, much smaller and have smaller variability when interval boundaries are defined from the heat requirements (method 1) than when using calendar dates (method 2). Calendar dates produce the greatest deviation for the inflorescence and berry development intervals, significantly overpredicting the temperatures during these intervals. Moreover, for the ripening interval, calendar dates tend to underpredict the temperatures. Similarly, Fig. 5 shows that differences in precipitation are, on average, smaller and have smaller variability when interval boundaries are defined by using method 1 than when using method 2.

Figure 6 shows the yearly mean temperature in each growth interval when computed using intervals with boundaries defined according to the method based on historical phenology data vs intervals with boundaries defined according to each of the two alternative methods. For each growth interval, regression lines were plotted for the series representing historical data vs heat requirements (method 1) and for the series representing historical data vs calendar average dates (method 2). The results show a very high level of association between the temperature series obtained from growth intervals with boundaries defined using *historical phenology dates* and corresponding temperature series obtained from growth intervals with boundaries defined using *experimental heat requirements* (R^2 values of 0.99, 0.56, 0.96, and 0.91).

Figure 7 shows the yearly values of accumulated precipitation in each growth interval when computed using intervals with boundaries defined according to the method based on



a) End-of-Dormancy b) Inflorescence Development c) Berry Development d) Ripening

Fig. 4 Mean temperature differences for methods 1 and 2 growth intervals from reference growth intervals

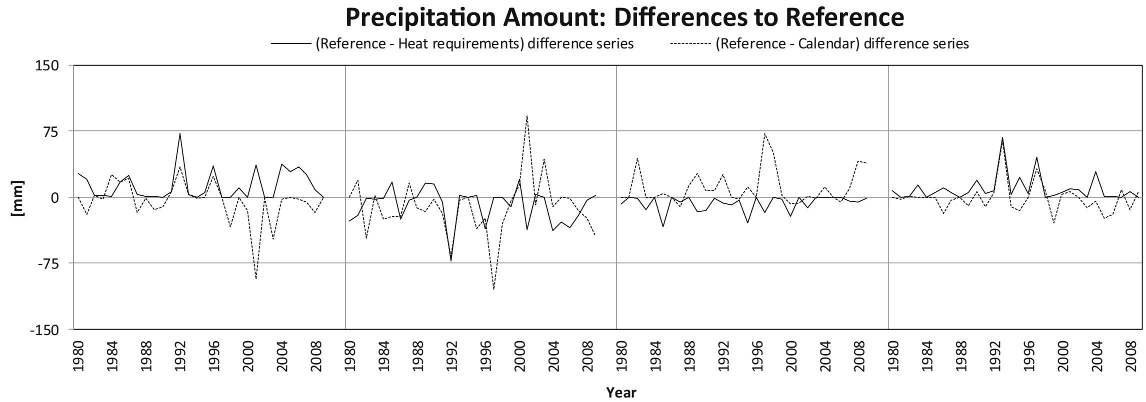


Fig. 5 Precipitation amount differences for methods 1 and 2 growth intervals from reference growth intervals

historical phenology data vs intervals with boundaries defined according to each of the two alternative methods. Regression analysis was conducted for the series shown in Fig. 7, and the results show that growth intervals with boundaries based on heat requirements are able to better estimate accumulated precipitation during growth intervals compared to boundaries defined using phenology historical dates, similarly to the results found with the estimation of mean temperatures.

The results shown in Figs. 6 and 7 exhibit that there is a much higher agreement between temperature and precipitation series between growth intervals with boundaries defined using grapevine experimental heat requirements and growth intervals with boundaries defined using historical phenology observed dates. A method that is able to obtain weather profiles similar to those obtained by using historical yearly data should be preferred in the absence of observations.

Relationships between vintage quality, phenological event dates, and growth interval lengths

The usefulness of defining the growth intervals based upon heat requirements (Table 5) was examined with an analysis of the best and worst vintages in the Douro Valley during 1980–2009. The analysis followed the previous description of the growing season partitioned into four smaller growth intervals bounded by January 1, budburst, flowering, *véraison*, and maturity. The quality of the Port wine vintages was assessed by means of the consensus ranking described in "Grapevine phenological data", with the best vintage assigned a value of 1 (ranked 1st) and the worst vintage with a value of 30 (the highest rank). We first analyzed all series with the ordinal dates of the main phenological events and growth interval lengths for normality, using the Shapiro-Wilk test, and for homoscedasticity, using the White test. The hypotheses of normality and of homoscedasticity were not rejected for any of the series analyzed, using a significance level of 5 %.

Differences between the average dates of the main phenological events in the top n vintages and in the bottom n vintages were evaluated using t tests. Using a significance level of 10 %, the average dates for top n vs bottom n vintages with $6 \leq n \leq 15$were examined. The results show that there are significant differences in budburst dates between the top and bottom vintages for $6 \leq n \leq 10$ (Fig. 8a). For flowering dates, significant differences between the average dates of the top and bottom vintages for $6 \leq n \leq 10$ were also found (Fig. 8b). Significant differences between top and bottom vintages for *véraison* dates ($6 \leq n \leq 9$) and maturity dates ($6 \leq n \leq 7$) were also found (Fig. 8c, d, respectively). These results here show that the best and worst vintages can be differentiated by the timing of the main phenological events. For each phenological event, earlier timing typically results in higher ranked vintages (5–10 days earlier than bottom ranked vintages). However, after the top 7 to 10 vintages, the differentiation becomes less evident. This could be an indication that average vintages tend to have numerous variations in plant growth due to greater variability in weather during the season.

A similar analysis was performed in order to assess if the lengths of the growth intervals bounded by January 1 and budburst (end of dormancy interval), by budburst and flowering (inflorescence development interval), by flowering and *véraison* (berry development interval), and by *véraison* and maturity (ripening interval) in top n vintages are different from corresponding lengths in bottom n vintages. Results show that, regarding the length of the end dormancy interval, there are significant differences between the average lengths of top n vintages when compared to bottom n vintages for $6 \leq n \leq 10$ and that, regarding the length of the berry development interval, there are significant differences between the average lengths of top n vintages when compared to bottom n vintages for $6 \leq n \leq 8$. Interestingly, while the length of the end dormancy interval is shorter in better vintages, the length of the berry development interval is shorter in worse vintages indicating that cool temperatures in the flowering to *véraison* period tend to promote quality (Fig. 9). For the inflorescence development

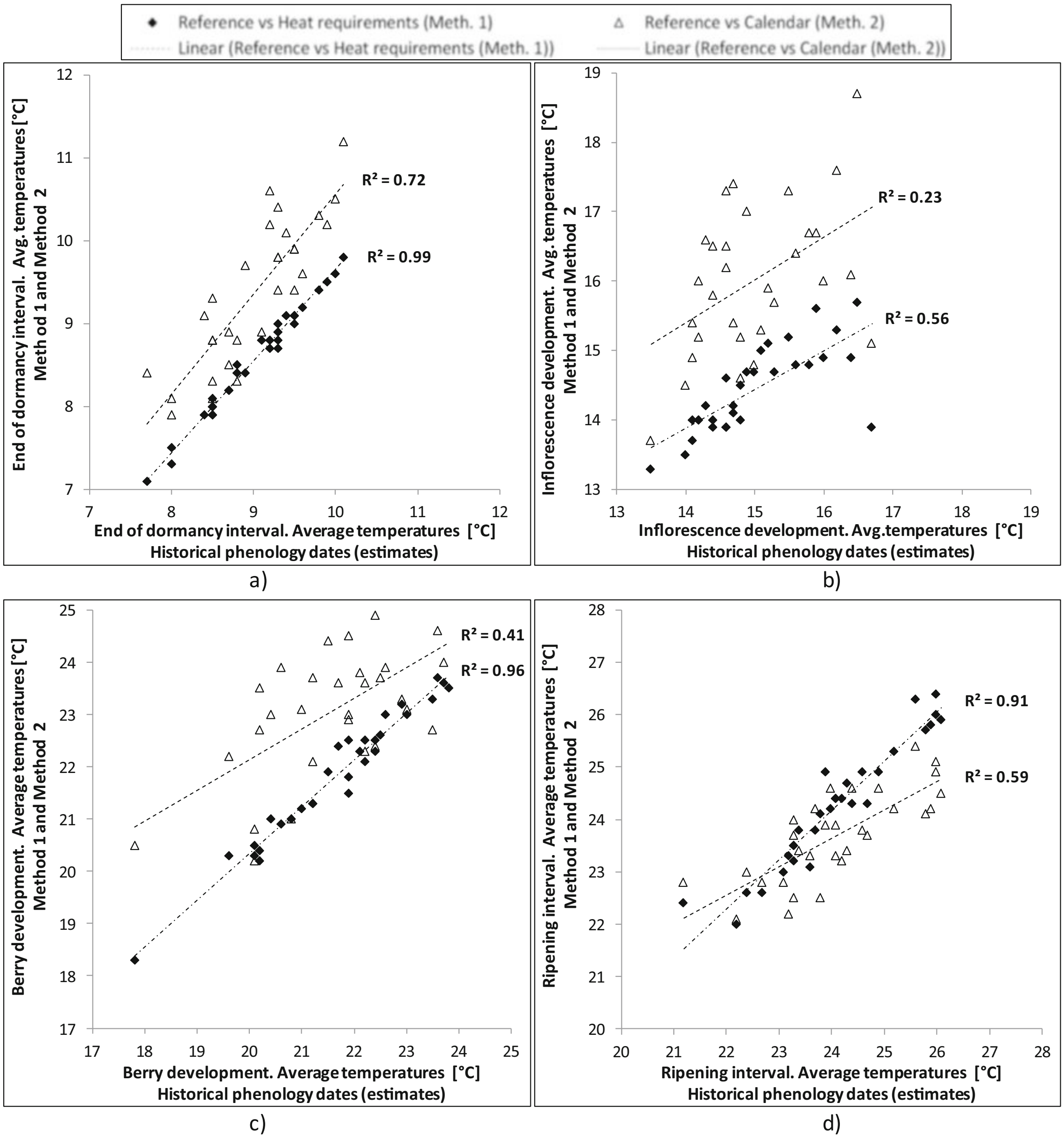


Fig. 6 Plots of mean temperature for growth intervals with boundaries defined using historical phenology dates vs corresponding values for growth intervals with boundaries defined by method 1 and method 2: **a** end of dormancy interval, **b** inflorescence development interval, **c** berry development interval, and **d** ripening interval

interval and for the ripening interval, no significant differences in length were identified between better and worse quality vintages.

The dates of the four main phenological events of the top six and bottom six vintage quality years and the generally accepted typical dates for the main phenological events (dash-dot line) are shown in Fig. 10. It is interesting to note the almost perfect separation of the top six and bottom six years. The best years have a clear tendency to start the growing season earlier. The one exception is 1990 (triangular icon b6, in Fig. 10), which experienced the earliest budburst during the time period. The overall weather/climate profile of 1990 would suggest that it was one of the best years, but budburst was possibly too early and the ripening season was relatively short. In summary, the results suggest that an early budburst is beneficial unless it is too early and/or followed by a cooler growing season. It is interesting to note that the 1984 and 1990 vintages, both belonging to the bottom six vintages during 1980–2009, have a very different phenological behavior. The 1984 vintage was a much delayed year (in all phenological events) and resulted in one of the worst vintages, and 1990 was a very early year (in all phenological events) and still one of the worst vintages. Furthermore, the average typical dates for the main phenological events (dash-dot line in Fig. 10) is

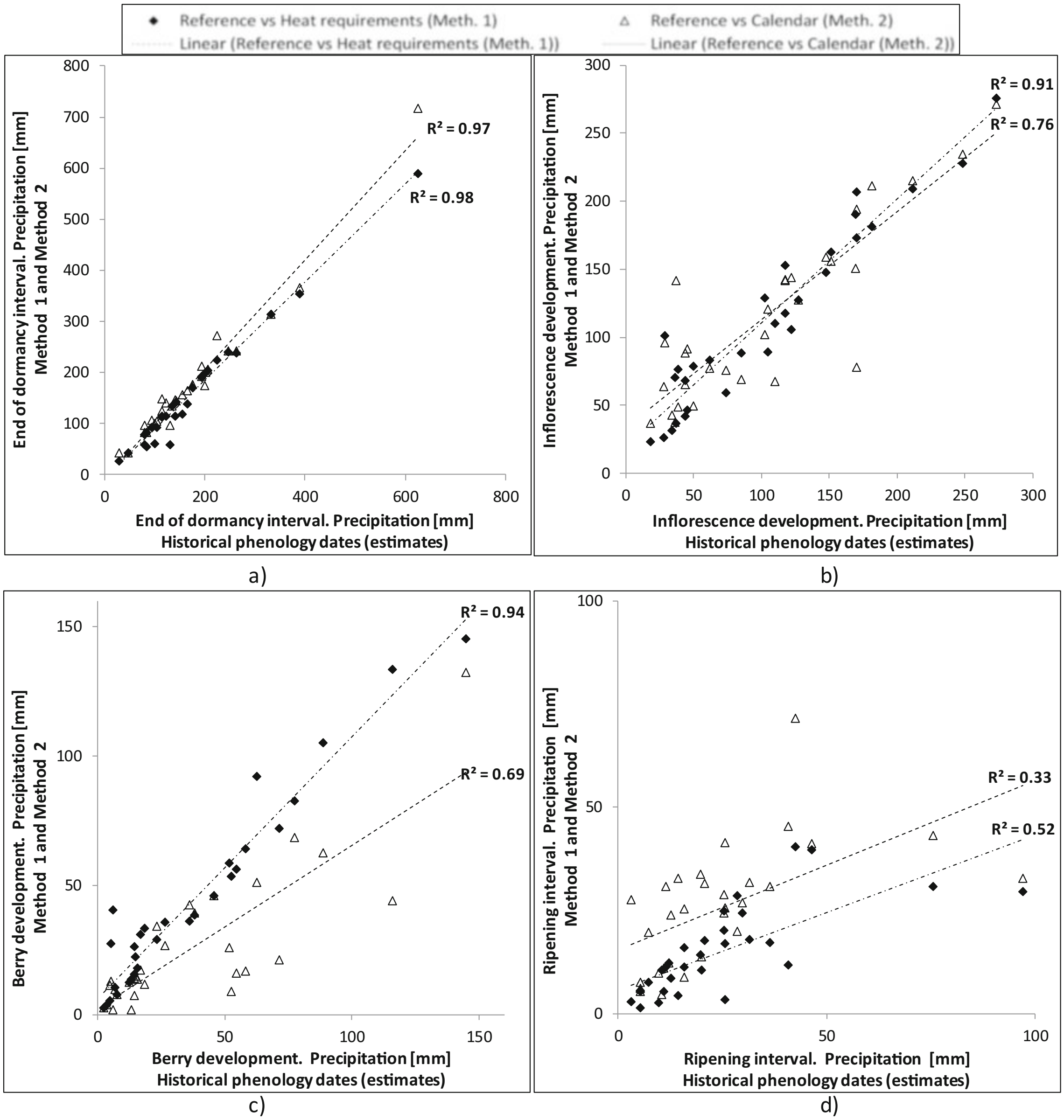


Fig. 7 Plots of accumulated precipitation for growth intervals with boundaries defined using historical phenology dates vs corresponding values for growth intervals with boundaries defined by method 1 and method 2: **a** end of dormancy interval, **b** inflorescence development interval, **c** berry development interval, and **d** ripening interval

closer to the worse vintages than to the best vintages which is further confirmation of the limitations of partitioning the growing season according to typical phenology average dates. Overall, the results show that vintage quality is strongly related to phenological timing.

Phenological characteristics and trends during 1980–2009

It was shown in the previous section that the method for partitioning the growing season into smaller intervals based on grapevine heat requirements (method 2) is able to mirror closely the dates of the historical phenological events. In this section, we analyze the evolution of the main phenological event dates and of the corresponding growth interval lengths, throughout the 30 years during 1980–2009, when phenological events are defined by grapevine experimental heat requirements.

A graphical representation of the amplitude of the boundaries of the main grapevine phenological events in the Douro Valley during 1980–2009 is shown in Fig. 11. The moments when the main events occur as well as the length of the interval between these events are good indicators of the overall vintage temperature profile.

The distribution of the dates in which each of the four main events occurred is as follows: the budburst

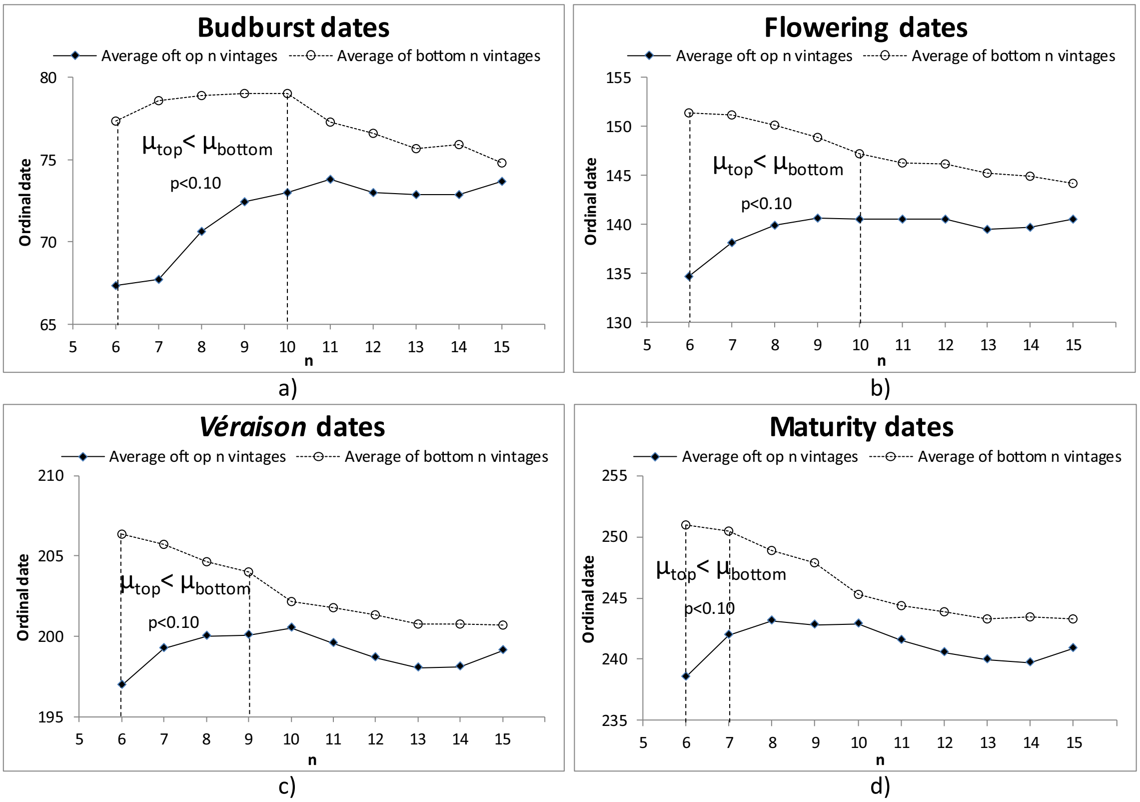


Fig. 8 Differences in dates of major phenological events between top *n* vintages and bottom *n* vintages: **a** budburst, **b** flowering, **c** *véraison*, and **d** maturity dates. Top vintages are all earlier with the significant differences shown by the *vertical dashed lines*

event median date is March 12 (72 OD) with an interquartile range of 14.3 days, the flowering event median date is May 20 (140 OD) with an interquartile range of 14.0 days, the *véraison* median date is July 17 (199 OD) and exhibits the smallest variability of the four events with an interquartile range of 8.8 days, and the maturity event median date is August 27 (240 OD) with an interquartile range of 10.8 days.

The distribution of the lengths of the four growth intervals and of the growing season is as follows: the end of dormancy interval median length is 72 days with an interquartile range of 14.3 days, the inflorescence development interval median length is 68 days with an interquartile range of 13.8 days, the berry development interval median length is 56 days with an interquartile range of 7.8 days, the ripening interval has a median length of 42 days and the smallest variability in interval lengths with an interquartile range of 5.0 days, and the growing season median length is 168 days with an interquartile range of 13.8 days. During this period, the range between the shortest and longest growing season was 50 days

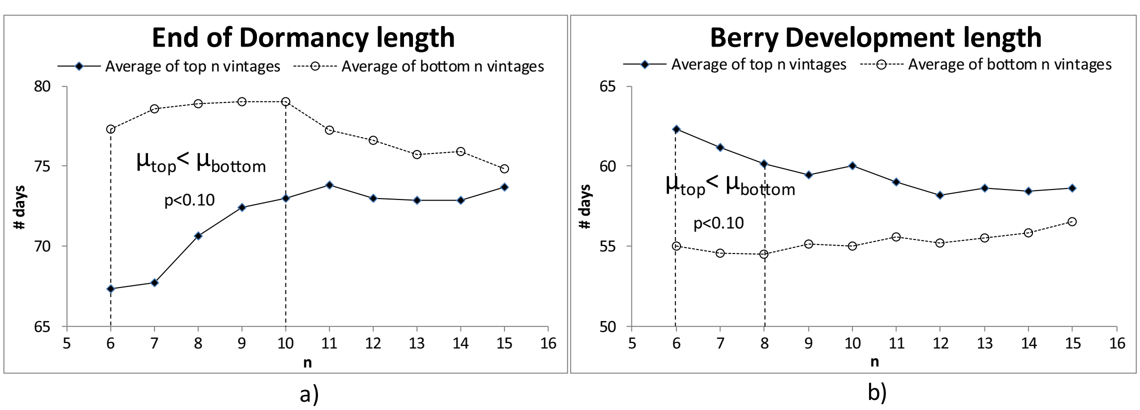


Fig. 9 Differences between growth intervals lengths of top *n* vintages and bottom *n* vintages. Only growth intervals with significant differences (*vertical dashed lines*) between lengths top *n* vintages and bottom *n* vintages are shown

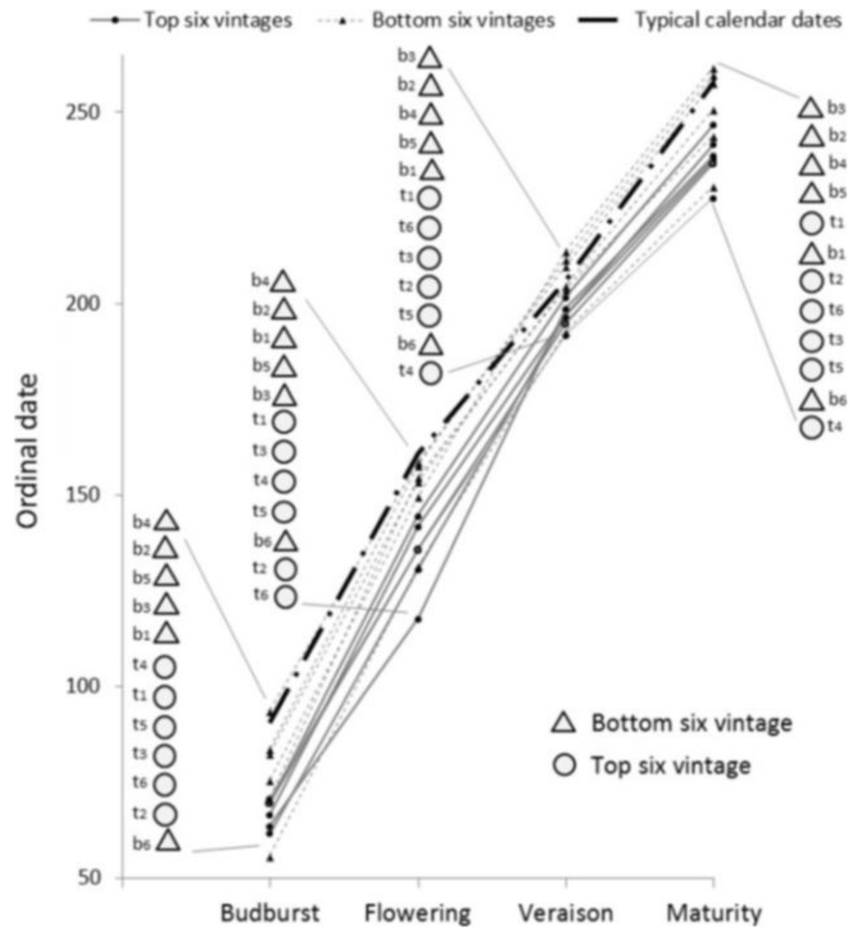


Fig. 10 Phenology calculated using grapevine heat requirements (method 2) for the six best (*open circles* and *t*) and for the six worst (*open triangles* and *b*) vintages for the Douro Valley during 1980–2009. Typical phenology calendar dates for the Northern Hemisphere are shown (*dash-dot line*) for comparison purposes

with the shortest occurring in 2006 (143 days) and the longest occurring in 1983 (193 days).

It is interesting to note that during 1980–2009, the dates of the four major phenological events show a tendency for occurring earlier (see Fig. 12). The estimated dates of the phenological events reveal statistically significant decreasing trends (*t* test, $p<0.04$), confirming that there is a tendency for an earlier grapevine physiology driven by changes in heat accumulation in the region (Jones and Alves 2012). During the time period, the events have trended 4.2 to 7.5 days earlier per decade, with the maturity dates changing the most.

For the length of the growth intervals, inflorescence development, berry development, and ripening intervals showed no significant trend during 1980–2009. However, the analysis of the length of the end of dormancy interval (from January 1 to budburst) that is coincident with the date of budburst, in 1980–2009, revealed a statistically significant decreasing trend (*t* test, $p=0.04$). Overall budburst today is occurring, on average, 13 days earlier than in the early 1980s.

The earlier phenological timing is related to an increase in temperatures in the Douro Valley in 1980-2009. Monthly regressions of daily maximum and minimum temperatures, using the 30-year data series, showed in detail how temperatures evolved from 1980 to 2009. For every month, the slopes of regression lines were calculated and the hypothesis of being equal to zero was tested. Only slopes significantly different from zero (*t* test, *p* value <0.05) were considered as rates of change of T_{max} or T_{min}. Results show that the average

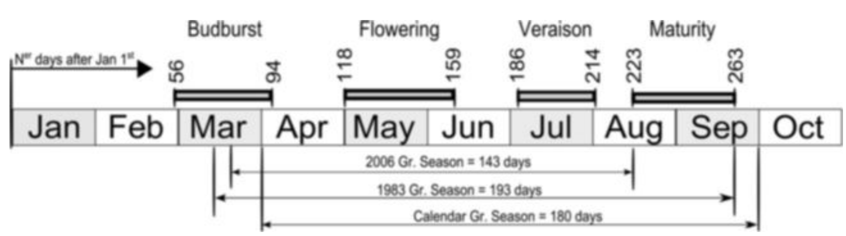


Fig. 11 Major phenological event dates and intervals for grapevines grown in the Douro Valley during 1980–2009

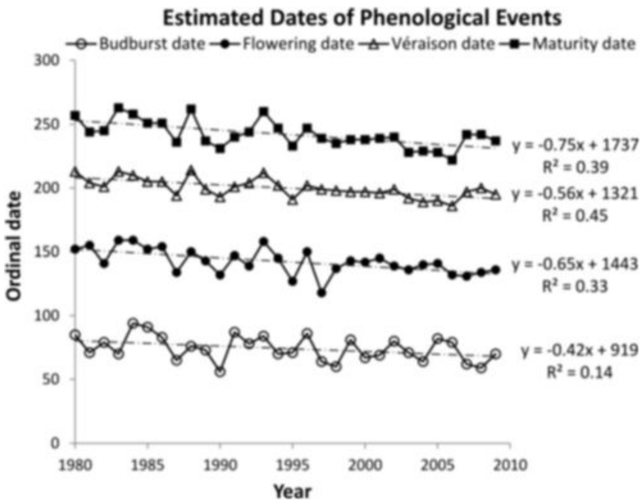


Fig. 12 Trends in the grapevine phenological event dates (estimated) in the Douro Valley during 1980–2009

temperatures in the growing season period increased on average 2.3 °C from April to June, with the most significant warming coming in May and June where an average temperature increase over 2.5 °C has been observed (Fig. 13). The increase in the average temperatures in this period is explained by a significant increase in both maximum and minimum temperatures which increased in every month from April to June. An increase in average temperatures in July to September was also observed but at a lower magnitude than in April through June. On average, the increase in July to September was 0.7 °C, explained exclusively by an increase in minimum temperatures (Fig. 13). The number of days with average temperatures below 10 °C (the typical base temperature for degree-days) was similar in every month from January to May (average values 25, 18, and 7 days) with the exception of a significant decline of 5 days in April, from 5 days to 0 days, when comparing average regression values of 1980 to values of 2009 (not shown).

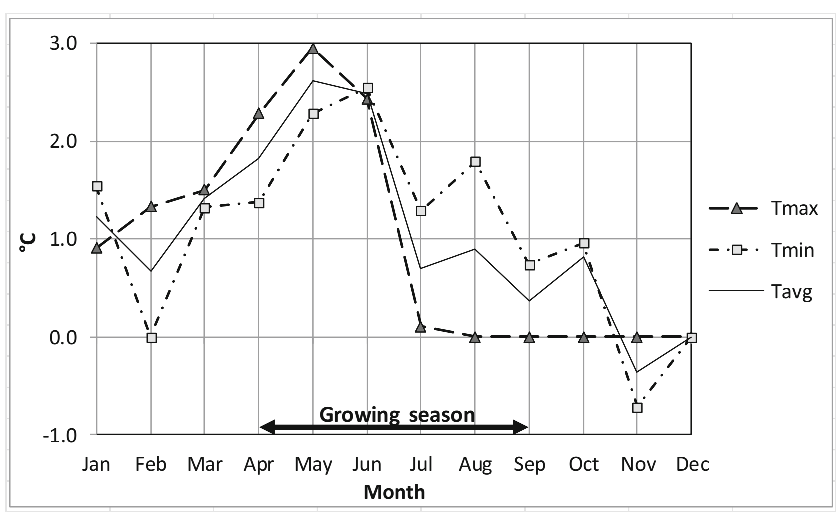
Conclusions

Partitioning the grapevine growing season into smaller growth intervals is necessary for studying the relationships of wine quality to weather and climate variability. When no data on historical phenological dates are available, the partitioning of a growing season may be achieved by defining interval boundaries using different methods: (i) by mean values of heat requirements to reach each main phenological stage and (ii) by generalized calendar average dates.

In general, it is difficult to have access to consistent data with the dates of the four main developmental stages for grapevines that covers a whole region for an extended period. However, this research was able to obtain the average dates of the main phenological events for the city of *Régua* and yearly data for the *Touriga Franca* variety from 2001 to 2012 at *Quinta de Santa Bárbara*, near the village of *Pinhão*, in the Douro Valley of Portugal. These data were used to estimate the observed yearly dates of the four main developmental phenological events for the region.

Using the available data, the research assessed the accuracy of determining the main growth intervals by means of the heat requirements of the main phenological events and by means of generalized calendar average dates. The results show that when there are no records on the actual dates of the phenological events, the best option is to use accumulated heat (growing degree-days) to determine the growth events and intervals between events. Partitioning based on calendar dates should be used only when there is no knowledge of grapevine

Fig. 13 Differences in values of minimum temperature (T_{min}), maximum temperature (T_{max}), and average temperature (T_{avg}) for every month, when comparing average regression values of 2009 to values of 1980



heat requirements or when there are no daily records of temperatures.

In addition, this research also assessed the ability of growth intervals based on grapevine heat requirements (method 1) to differentiate the best and worst quality vintages defined by ranked ratings. Results reveal that the best and the worst vintages exhibit a clearly different profile of the growing season phenological timing and therefore weather and climate characteristics that influence this timing. The best vintages show a clear tendency toward earlier events. In addition, significant differences were found in the length of the end of dormancy interval (the time from January 1 to budburst), which is typically shorter in better quality vintages, while the length of the berry development interval (the time from flowering to *véraison*) is typically longer in better quality vintages.

Finally, the analysis of the evolution of the growth events and interval characteristics over time in the Douro Valley revealed that there was a statistically significant tendency toward earlier events during 1980–2009 that is related to an increase in average temperature. The budburst date is now, on average, 13 days earlier than in the early 1980s while flowering is 17 days earlier, *véraison* 20 days earlier, and maturity 23 days earlier. In terms of growth intervals, only January 1 to budburst trended shorter due to the fixed starting date, while the other growth intervals shifted earlier but did not shorten significantly over the time period. These results show that climatic changes are promoting earlier grapevine phenological events in the region as shown by Jones and Alves (2012) and Jones (2012).

There are many signs that climate is changing including increasing evidence of sea level rise, global temperatures increasing, warming oceans, shrinking ice sheets, declining Arctic sea, glacial retreat, and an increased frequency of extreme events (NASA 2013). Previous research has shown that both climate variability and change play strong roles in wine production and quality in many regions (e.g., Jones et al. 2005 and others). A better understanding of the way weather and climate factors affect the variability of vintages will potentially be invaluable for decreasing the vulnerability of producers in wine regions and ultimately providing insights in appropriate adaptive measures that will aid in the economic sustainability of wine regions. The results obtained in this work highlight the need for regional monitoring of grapevine growth stages and maintaining consistent historical phenological data for a significant period. Better phenological data and better understanding of the roles weather and climate play in phenological timing, and therefore vintage quality and production variability, will be useful to the winemakers of the Douro Valley and other wine regions.

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