WINEGRAPE PHENOLOGY AND TEMPERATURE RELATIONSHIPS IN THE LISBON WINE REGION, PORTUGAL

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Abstract

Aim : To investigate the characteristics, relationships and trends in the phenology of four winegrape varieties and associated temperature relationships in the Lisbon wine region (LWR), between 1990 and 2011.

Methods and results : Budburst, flowering and véraison dates of red (Castelão and Aragonez, syn. Tempranillo) and white (Chasselas and Fernão Pires) varieties were taken from an experimental vineyard in the LWR. Harvest dates were determined based on a similar maturity level for all varieties. From these data, varietal characteristics, temporal trends as well as relationships between phenology and temperature were assessed through stepwise multivariate linear regressions. Flowering was the most sensitive to temperature in the preceding months (March-April). Differences/similarities between the phenological timing of the different varieties are presented. With few exceptions, no trends were found in phenophases over the 1990-2011 period, whereas several significant negative slopes were displayed for phenological intervals, suggesting a role for accumulated thermal effects in phenological timing. Strong correlations were observed between phenophases, especially between flowering and véraison.

Conclusion : The study highlights the key role played by temperature on phenology, particularly during springtime. Furthermore, an increase in temperature during that period will cause an advance in the timing of the following phenological events. Given the significant trends found, phenological shifts may occur in the long term, emphasizing the need to assess varietal characteristics and responses to regional climate.

Significance and impact of the study : The present work is the first attempt to systematically examine temporal trends in phenology and corresponding relationships with temperature in a Portuguese viticultural area, providing valuable information on the development and suitability of grapevine varieties, which determine viticultural practices and winegrower's income.

Key words : *Vitis vinifera* L., phenology, climate variability, Lisbon wine region, Portugal

Résumé

Objectif : Étudier les caractéristiques, les relations et les tendances de la phénologie de quatre variétés de raisin de cuve et leurs relations avec la température dans la région viticole de Lisbonne (LWR), entre 1990 et 2011.

Méthodes et résultats : Les dates de débourrement, floraison et véraison de variétés de raisins rouges (Castelão et Aragonez, syn. Tempranillo) et blancs (Chasselas et Fernão Pires) ont été relevées dans un vignoble expérimental dans la LWR. Les dates de récolte ont été déterminées en fonction d'un niveau de maturité similaire pour toutes les variétés. A partir de ces données, les caractéristiques variétales, les tendances temporelles ainsi que les relations entre la phénologie et la température ont été évaluées à travers un modèle de régression linéaire multivariée. La floraison était le stade phénologique le plus sensible à la température des mois précédents (mars-avril). Les différences/similitudes entre le calendrier phénologique des différentes variétés sont présentées. Sauf quelques exceptions, aucune tendance n'a été observée dans les stades phénologiques, alors que plusieurs tendances significativement négatives ont été observées pour des intervalles phénologiques, ce qui suggère l'accumulation d'effets thermiques au cours du cycle végétatif. De fortes corrélations entre les phases phénologiques sont présentées, en particulier entre la floraison et la véraison.

Conclusion : Cette étude met en évidence le rôle clé joué par la température sur la phénologie, en particulier au printemps. En outre, l'augmentation de la température au cours de cette période entraînera une avancée des stades phénologiques suivants. Compte tenu de certaines tendances significatives observées, des changements phénologiques peuvent survenir à long terme, ce qui souligne la nécessité d'évaluer les caractéristiques variétales et les réponses au climat régional.

Signification et impact de l'étude : Cette recherche est une première tentative d'étudier systématiquement les tendances temporelles de la phénologie et les relations correspondantes avec la température dans une région viticole portugaise, fournissant des informations précieuses sur le développement et la viabilité des variétés, qui déterminent les pratiques viticoles et le rendement des viticulteurs.

Mots clés : *Vitis vinifera* L., phénologie, variabilité climatique, région viticole de Lisbonne, Portugal

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INTRODUCTION

It is widely acknowledged that vitiviniculture is mainly governed by weather and climate conditions (Due *et al.*, 1993 ; Jackson and Lombard, 1993 ; Keller, 2010 ; Fraga *et al.*, 2013a). In fact, *Vitis vinifera* L. is a perennial and deciduous crop, whose vegetative cycle, morphologically described by phenological stages, is mostly driven by air temperature. Precipitation and radiation are also important, though to a lesser extent (Jones, 2003 ; Bock *et al.*, 2011 ; Tomasi *et al.*, 2011 ; Urhausen *et al.*, 2011). After a period of chilling temperatures in winter for breaking dormancy, the growing season begins with budburst in early spring. A cumulative effect of temperatures above a threshold of 10°C (base temperature) is the classical thermal requirement for this event to take place (Winkler *et al.*, 1974). The following main events are flowering, véraison (berry softening and colour change) and harvest (with fruit ripening in summer), during which warm temperatures (dry and stable atmospheric conditions) are required for balanced crop yield and wine quality (Jones and Davis, 2000a ; Santos *et al.*, 2011, 2013). Later, the vines lose their leaves (leaf fall in autumn). Mild temperatures and considerable precipitation totals during the dormant period are critical for the next growing season, particularly in Mediterranean winegrowing regions (Magalhães, 2008). All these climatic requirements are reflected in the global geographic distribution of this species, preferably located where growing season mean temperatures range from 12 to 22°C (Jones, 2006). Within these boundaries are the typical Mediterranean climates, which includes the Portuguese winegrowing areas, despite important regional differences and strong inter-annual variability that may significantly influence winegrape phenology (Fraga *et al.*, 2012). In addition, the timing of each phenophase differs according to each grapevine variety and is generally tied to local thermal conditions (e.g., flowering and véraison ; Parker *et al.*, 2011). Indeed, phenological models based on temperature accumulations above a base temperature between events, such as Growing Degree Days (GDD), have been extensively reported in the literature (e.g., Chuine *et al.*, 2003 ; Jones, 2003). More complex models using different threshold values and chilling requirements have also been developed (Garcia de Cortázar-Atauri *et al.*, 2009 ; Caffarra and Eccel, 2011). Taking into account these heat requirements, different derived (bioclimatic) indices have been used for viticultural climatic zoning and inter-regional and global comparisons (Malheiro *et al.*, 2010 ; Fraga *et al.*, 2013a,b). Other studies linking phenology and climate variability (especially temperature) used temperature averages rather than summations (Grifoni *et al.*, 2006 ; García-Mozo *et al.*, 2010 ; Marta *et al.*, 2010 ; Bock *et al.*, 2011 ; Tomasi *et al.*, 2011) in order to avoid correlations between accumulated values and elapsed time (Due *et al.*, 1993 ; Jones and Davis, 2000b ; Urhausen *et al.*, 2011).

Most studies that addressed these links have reported earlier phenophase dates, shorter phenological intervals and warmer grape maturation periods, suggesting that these changes are mostly likely due to the temperature rise observed in recent years (Jones and Davis, 2000b ; Duchêne and Schneider, 2005 ; Jones *et al.*, 2005 ; Bock *et al.*, 2011 ; Tomasi *et al.*, 2011 ; Urhausen *et al.*, 2011). Furthermore, phenological changes are projected to be particularly striking in the upcoming decades due to warming trends (Webb *et al.*, 2007 ; Duchêne *et al.*, 2010 ; Caffarra and Eccel, 2011). Therefore, shifts in grapevine varieties, wine quality and typicity, and even in the location of the main winegrowing regions may occur in the long term (Malheiro *et al.*, 2010 ; Santos *et al.*, 2012 ; Fraga *et al.*, 2013b). Most importantly, these authors projected detrimental impacts in most wine regions of southern Europe, which would require short-term measures (e.g., irrigation ; Ferreira *et al.*, 2012) to cope with environmental stresses.

The phenological characteristics of individual grapevine varieties as well as their responses to climate are of utmost importance for activity planning and decision making in viticulture. Indeed, they may have direct impacts on vine yield and wine production, and, ultimately, on winegrower's income (Magalhães, 2008). Therefore, the present study evaluated the influence of temperature variability on the phenology of four winegrape varieties in the Lisbon wine region (LWR) of south-western Portugal. In addition, the relationships between the onset and duration of the main phenological stages and their trends were analysed. To our knowledge, this is the first attempt to systematically examine temporal trends in phenology and corresponding climate links in a Portuguese viticultural area. As the selected region is the second most important with respect to production volume (after the Douro Valley), it also plays a central role in the Portuguese economy (IVV, 2011).

MATERIALS AND METHODS

1. Location and climate data

The study was carried out in the LWR (former Estremadura region), consisting of a coastal north-south strip about 30 km wide stretching from just north of Lisbon to central Portugal (Figure 1). The winegrowing area is characterized by a Mediterranean climate (i. e., warm temperate climate with a dry and warm summer; Kottek *et al.*, 2006), with a noteworthy Atlantic influence. The 'WorldClim' database (Hijmans *et al.*, 2005), which provides gridded data (with spatial resolution of about 1 km at the Equator) of monthly precipitation and maximum, minimum and mean air temperatures over 1950-2000, was used for the description of regional climate conditions. These variables were then extracted over the target area (8183 grid cells), overcoming the considerable lack of data provided by the few weather stations located within the region.

At the vineyard level, two sets of daily maximum, minimum and mean air temperature records were used for the calculation of monthly values. The first set (1999-2011) was recorded from a standard meteorological weather station close to the experimental site (Dois Portos: 39.0ºN, 9.2ºW, 110 m asl). As this set did not cover the entire 22 years of the study period (1990-2011), daily data from the Lisbon meteorological station (Lisboa/Geofísico: 38.7°N, 9.1°W, 80 m asl) were selected over the study period. By applying linear regressions between these two datasets in their common period (1999-2011), high coefficients of determination were obtained for monthly maximum, minimum and mean temperatures ($0.96 \leq R^2 \leq 0.99$). This result highlights the similarity of the inter-annual climate variability within the LWR, which is fundamentally forced by large-scale atmospheric patterns (Santos *et al.*, 2011). Using the regression coefficients from these linear regression equations, a third and complete set of monthly (maximum, minimum and mean) temperature data was estimated for Dois Portos in the extended period of 1990-2011 (reconstructed series); the correlation coefficients between the raw and the reconstructed time series were ≥ 0.98 for the three variables in their common period (1999-2011). The yearly evolution of maximum, mean and minimum temperatures (reconstructed series) for the four trimesters is shown in Figure 2. Even though these reconstructed series are not free of bias, the very high correlation coefficients referred to above suggest that their inter-annual variability was reliably reproduced, which is by far the most important property when modelling the inter-annual variability of phenological variables. In effect, this methodology allows overcoming an important limitation: the absence of simultaneous meteorological and phenological data in the same location and over a relatively long time period. However, these data constraints prevented the use of daily temperatures. Therefore, temperature thresholds (Jones and Davis, 2000b), varietal thermal requirements (Duchêne *et al.*, 2010; Parker *et al.*, 2011) and derived indices (Jones, 2003; Fraga *et al.*, 2013a) were not computed in the present work. The monthly series are then only related to grapevine phenology. Although precipitation was also considered in a first exploratory study, it presented no statistically significant correlations with phenological stages (95 % confidence level) and was thus discarded from the analysis (not shown).

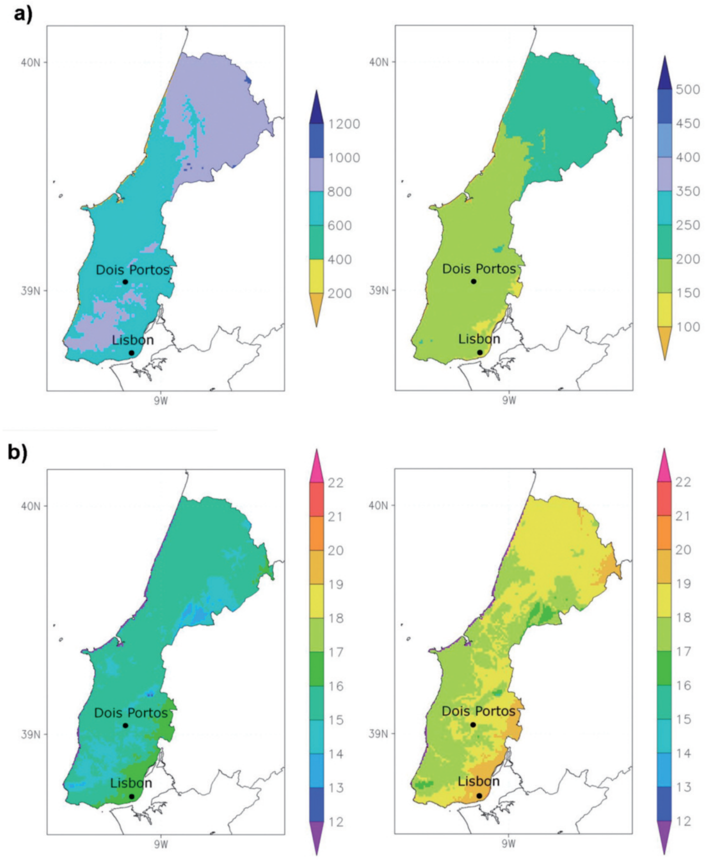

Figure 1 - (a) Average annual (left panel) and April - September (right panel) precipitation (in mm) for the 1950-2000 period, Lisbon wine region, Portugal. (b) Same as in a) for air temperature (in ºC).

2 Plant material and phenology

The dates of key phenophases of two red (Aragonez and Castelão) and two white (Chasselas and Fernão Pires) *Vitis vinifera* L. varieties were obtained from the Portuguese national ampelographic collection at the state laboratory 'Instituto Nacional de Investigação Agrária e Veterinária' in Dois Portos (which includes the former 'Estação Vitivinícola Nacional'). These varieties cover the longest period of phenological records within the collection. The vineyard, which covers about 2 ha and 724 accessions or botanical clones, aims to preserve the native Portuguese varieties, allowing characterization,

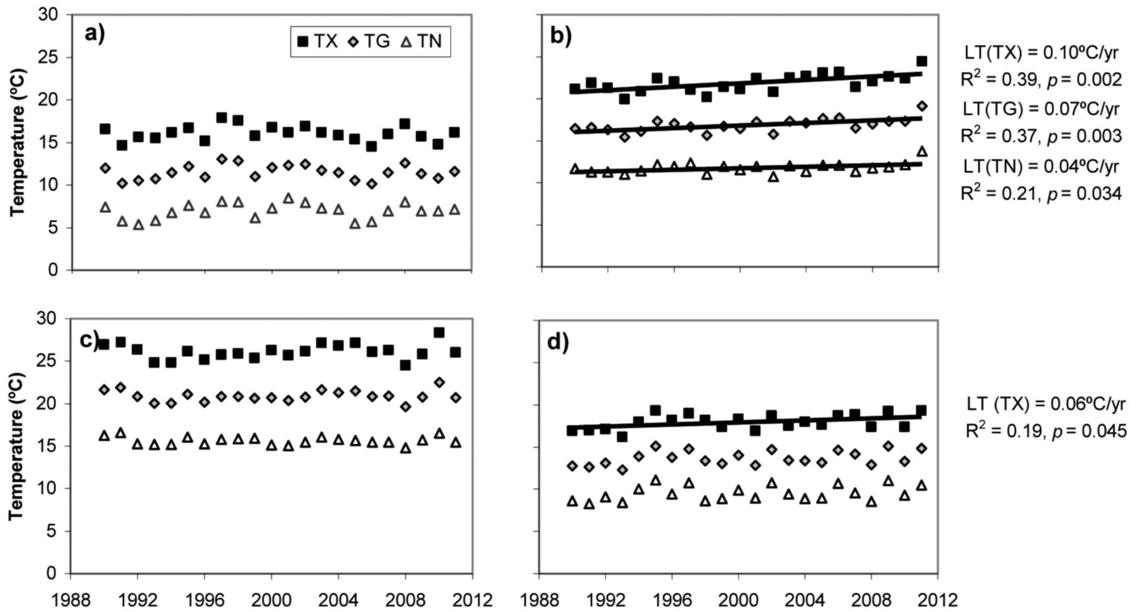

Figure 2 - Yearly evolution (1990-2011) of maximum (TX), mean (TG) and minimum (TN) temperatures (reconstructed series) for (a) winter (Jan-Feb-Mar), (b) spring (Apr-May-Jun), (c) summer (Jul-Aug-Sep) and (d) autumn (Oct-Nov-Dec) in Dois Portos, Portugal.

Straight lines represent linear regressions for significant trends, LT the trends, and R^2 the coefficients of determination. *p*-values < 0.05 are shown.

identification and synonymy/homonymy study. It has also the goal of being used as a reference collection for varieties and rootstocks grown in Portugal, including those widely planted worldwide. The experimental vines are trained on vertical trellis at a plant density of about 3200 vines/ha and grafted onto SO4 rootstock. The soil is classified as a calcic fluvisol (eutric) (FAO, 2006).

Castelão and Fernão Pires are two native winegrape varieties, typically planted in the study area. Aragonez (syn. Tempranillo) is largely grown in the Iberian Peninsula and Chasselas in Switzerland (where it is known as Fendant) and France (Magalhães, 2008). Regarding phenological precocity, budding ranges from early (Castelão, Chasselas and Fernão Pires) to average (Aragonez) and all are early ripening (Lopes *et al.*, 2008; Magalhães, 2008), though temperature sum requirements along the growing season may vary with variety and climate (Parker *et al.*, 2011). The observed date of budburst, flowering and véraison of the four varieties were monitored from 1990 to 2011 (22 years), except for Aragonez, for which no data was available for the first four years. These phenological stages were considered to occur when 50 % of the plants had reached a particular stage. Budburst, flowering and véraison correspond to stages 07, 65 and 81, according to the BBCH scale, respectively (Lorenz *et al.*, 1995). In addition, harvest dates (stage 89 on the BBCH scale) were available for the 1990-2011 period (except for the 1994 vintage). The white varieties were harvested when probable alcohol content of Fernão Pires fruits was about 11.5 % (vol.), which is considered as a reference, though Chasselas berries generally had lower probable alcohol content at harvest (not shown). A similar approach was carried out for the red varieties using Castelão as a reference (11.5 % vol.). For this purpose, berry samples from these varieties were collected from the end of August to early September (2-4 samplings) of every vintage. As the harvest date is generally considered as a 'false' phenophase influenced by weather conditions, oenological decisions and winery logistics (Petrie and Sadras, 2008), a comparison of harvest dates with similar level of ripeness was developed. Therefore, an estimated harvest date for each variety reaching a probable alcohol content of 11.5 % (vol.; hereafter designated as harvest) was defined by taking the linear rate of change in probable alcohol content during maturation. The observed phenological events were also used to derive the intervals between each event (budburst to flowering, budburst to véraison, flowering to véraison and véraison to harvest). The growing season length corresponds to the number of days between budburst and harvest.

3. Statistical analysis

Statistical analysis of phenology from the four varieties was undertaken using the *t*-Student's test in conjunction with the least significant differences of means. The results are then presented as mean estimates ± standard deviation, for inter-annual variability assessment. In addition, medians, interquartile ranges and outliers were determined. In order to examine linear dependencies between these variables, Pearson correlation coefficients were also computed. The differences between means and linear regression trends were assumed to be statistically significant at the 5 % level. A multivariate linear regression model (stepwise methodology) was applied (using a least-squares approach) to grapevine phenology using the full set of selected potential predictors (monthly maximum, minimum and mean temperatures separately and in combination) as independent variables.

RESULTS AND DISCUSSION

1. Climatic conditions

Average of annual total precipitation and mean temperature patterns within the LWR were 780 mm and 15.4ºC, respectively, over the 1950-2000 period (Figure 1). Typically, the northern hilly areas and the western coast were much wetter and cooler than the south-easternmost area (where Lisbon is located). Indeed, the average climatic conditions in Lisbon were warmer and drier than those typically found in the LWR. Furthermore, high elevation areas, such as in the Montejunto mountain range and the coastal strip (sea breeze influence), presented the coolest conditions. For the growing season (April-September), the area-mean temperatures were clearly higher than their annual means (nearly +3ºC) and the area-mean precipitation were significantly lower (nearly -600 mm), which is typical of the LWR Mediterranean climate. The remarkable seasonality in precipitation can be demonstrated at the experimental site (Dois Portos), where the long-term average precipitation from April to September was about 160 mm, which represents roughly 22 % of the total annual amount. At the same site, annual and growing season mean temperatures were 15.7 and 18.4ºC, respectively.

During the study period (1990-2011), relevant seasonal differences between years were found (Figure 2). In fact, there were summer periods (July, August and September) presenting anomalously high mean temperatures (e.g., 1990, 1991, 2003 and 2010, anomalies of +0.7-1.6ºC) and winter periods (January, February and March) presenting anomalously low mean temperatures (e.g., 1991, 1992, 2005 and 2006, anomalies ranging from -1.0 to -1.4ºC). Furthermore, significant temperature trends were displayed for autumn (maximum temperature) and springtime (Figure 2). Regarding the annual values (Figure 3), some years (e.g., 1995, 1997 and 2011) were anomalously warm (anomalies in the annual mean temperature of +0.6-0.8ºC), whereas others (e.g., 1992, 1993 and 1999) were anomalously cold (anomalies in the annual mean temperature from -1.1 to -0.4ºC). Significant positive trends were also found for the annual means of daily maximum and mean temperatures (+0.04-0.03ºC/yr, $p \leq 0.016$). This inter-annual variability is expected to have forced the whole phenology of the winegrapes in the LWR and to be reflected in the winegrape phenology of the study site in particular.

2. Characteristics and relationships in phenology

Overall, the time series of the main phenological events for the four selected winegrape varieties revealed a very similar behaviour, with clear inter-annual variability during 1990-2011 (Figure 4). Furthermore, median dates were quite similar to mean dates for each phenophase of each variety, but significant differences in means were found between varieties (not shown). However, the mean budburst date (March 14 ± 8 days) of Castelão, Chasselas and Fernão Pires did not differ significantly but was distributed over nearly one month, from February 27 (2001) to March 30 (2005) (Figure 4). On the other hand, this phenological event took place from March 8 (1998 and 2001) to April 6 (2005) for Aragonez, which was, on average, near a week later (March 20 ± 9 days) compared with the other three varieties, revealing its (mean) budburst precocity (Lopes *et al.*, 2008).

There were no significant differences between varieties in the mean flowering dates (May 20 ± 9 days), with a maximum about two/three weeks later

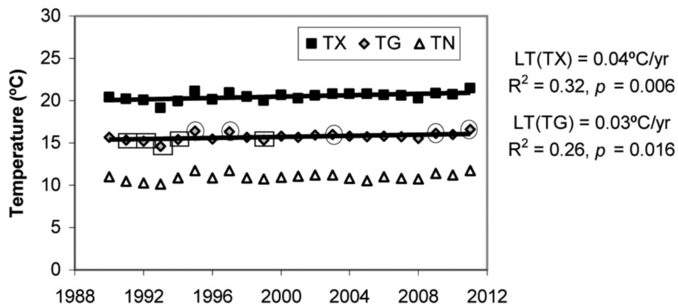

Figure 3 – Annual maximum (TX), mean (TG) and minimum (TN) temperatures (reconstructed series) for the 1990-2011 period in Dois Portos, Portugal.
Enclosed mean temperature symbols correspond to values that fell below first (squares) and above third (circles) quartiles. Straight lines represent linear regressions for significant trends, LT the trends, and R^2 the coefficients of determination. *p*-values < 0.05 are shown.

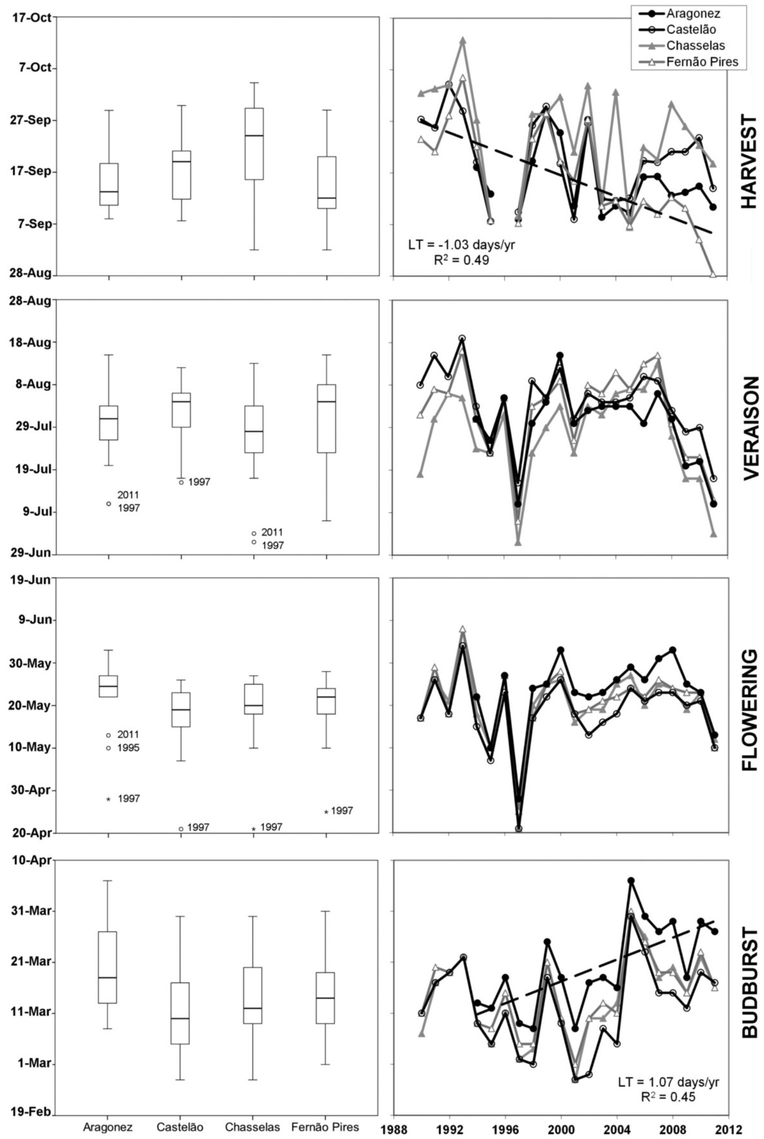

Figure 4 - On the left: Box plots of budburst, flowering, véraison and harvest dates of Aragonez, Castelão, Chasselas and Fernão Pires varieties from 1990 to 2011 in Dois Portos, Portugal.

Medians correspond to horizontal black lines within boxes, lower (upper) box limits to the first (third) quartiles and whiskers to the non-outlier maxima and minima. First (second) order outliers are indicated by circles (asterisks) and represent events above/below the box upper/lower limit by at least 1.5 (3.0) times the respective box height (interquartile range).

On the right: Time series of the same phenophases and varieties for the outlined period.

The dashed lines represent the linear regression for the budburst of Aragonez and harvest of Fernão Pires, LT represents trend, and R^2 represents the coefficient of determination.

(June 2-7). Outlier minima were also reported for all varieties in 1997 (April 24) that corresponded to an anomalously warm March-April period (anomaly of +2.8ºC in the two-month mean). Regarding the véraison dates, Chasselas presented higher range (42 days) compared with Castelão (34 days), but significant earlier onsets (July 27 ± 11 days and August 4 ± 8 days, respectively ; Figure 4 and Table 1). Despite no significant differences, Aragonez and Fernão Pires tended to onset maturation between the former two varieties. As previously, 1997 was an outlier for all varieties except Fernão Pires, and 2011 (anomaly of +3.0ºC in the April-May mean) was an outlier for Aragonez and Chasselas.

Average harvesting of Chasselas occurred around 10 days later compared with Aragonez and Fernão Pires (September 15 ± 8 days), which should be explained by its generally lower probable alcohol content (compared with the other three varieties) at harvest. Furthermore, Chasselas showed a high range (36 days), similar to Fernão Pires (38 days) but lower than

Table 1 - Means, standard deviations and linear trend parameters (R^2, *p*-value and annual trend) of main phenophase dates and corresponding intervals for the four varieties in Dois Portos, Portugal (1990-2011).

Variable	Variety	n	Mean	Std. Dev.	R^2	*p*-value	Trend (days/yr)
Budburst	Aragonez	18	Mar 20	9	0.45	0.002	+1.1
	Castelão	22	Mar 12	8	*ns*		
	Chasselas	22	Mar 14	8	*ns*		
	Fernão Pires	22	Mar 15	7	*ns*		
Flowering	Aragonez	18	May 23	9	*ns*		
	Castelão	22	May 18	8	*ns*		
	Chasselas	22	May 20	9	*ns*		
	Fernão Pires	22	May 21	8	*ns*		
Véraison	Aragonez	18	Jul 29	9	*ns*		
	Castelão	22	Aug 4	8	*ns*		
	Chasselas	22	Jul 27	11	*ns*		
	Fernão Pires	22	Aug 2	10	*ns*		
Harvest	Aragonez	17	Sep 15	6	*ns*		
	Castelão	21	Sep 20	8	*ns*		
	Chasselas	21	Sep 25	10	*ns*		
	Fernão Pires	21	Sep 16	10	0.49	<0.001	-1.0
Budburst to Flowering	Aragonez	18	64	9	*ns*		
	Castelão	22	67	8	*ns*		
	Chasselas	22	68	8	*ns*		
	Fernão Pires	22	67	8	*ns*		
Budburst to Véraison	Aragonez	18	131	12	0.45	0.003	-1.5
	Castelão	22	145	10	0.21	0.035	-0.7
	Chasselas	22	135	10	*ns*		
	Fernão Pires	22	140	10	*ns*		
Budburst to Harvest	Aragonez	17	179	11	0.51	0.001	-1.5
	Castelão	21	192	10	*ns*		
	Chasselas	21	195	12	0.24	0.023	-0.9
	Fernão Pires	21	185	13	0.49	<0.001	-1.4
Flowering to Véraison	Aragonez	18	68	6	0.67	<0.001	-0.9
	Castelão	22	78	5	0.40	0.002	-0.5
	Chasselas	22	68	8	*ns*		
	Fernão Pires	22	73	7	*ns*		
Véraison to Harvest	Aragonez	17	48	8	*ns*		
	Castelão	21	47	7	*ns*		
	Chasselas	21	60	13	*ns*		
	Fernão Pires	21	45	10	0.25	0.021	-0.7

ns, not significant

Aragonez (21 days) and Castelão (27 days). Importantly, despite environmental effects, days to berry maturity is also varietal dependent (Petrie and Sadras, 2008; Webb *et al.*, 2007, 2011) and genetically determined (Magalhães, 2008). An evidence of the latter characteristic might be found for Shiraz, syn. Syrah, in Australia, where over four consecutive seasons ripening parameters (°Brix and berry weight) were more closely correlated with the number of days after flowering than with GDD (McCarthy, 1999).

In the present study, an assessment of the intervals between the main phenological events showed high inter-annual variability (Table 1). Commonly, the flowering-véraison interval was the longest, but with relatively low inter-annual variability, followed by the budburst-flowering interval. The véraison-harvest interval presented the highest inter-annual variability. The budburst-flowering interval ranged from about 50 days for the shortest period in 1997 to about 79 days for the longest period in 2001, averaging 67 (±8) days during the study period. Conversely, significant differences between varieties were found for the growth period between flowering and véraison, with the exception (no difference) of Aragonez and Chasselas, where the averaged interval was 68 (±7) days, being also the shortest interval. On the other hand, Castelão revealed the longest average interval (78 ± 5 days), but with the lowest range (18 days). The length of the véraison to harvest interval (47 ± 8 days; Aragonez, Castelão and Fernão Pires) did not differ significantly between varieties, except for Chasselas, which was the last to reach maturity (60 ± 13 days), and ranged from 30 (year 2005) to 77 (year 2011) days.

The length from budburst to harvest is particularly important for defining the growing season period, which for Chasselas lasted from 160 (in 2005) to 209 (in 1990) days, with an average of 195 (±12) days. This last value was significantly extended compared to Fernão Pires (185 ± 13 days) and Aragonez (179 ± 11 days), but not to Castelão. Significant differences were also detected between Aragonez and Castelão for this same interval, which tended to have shorter and longer growing seasons, respectively.

Relationships between phenophases and varieties were clear (Table 2). Overall, significant correlations were observed between successive phenological stages; these were particularly strong between flowering and véraison ($r \geq 0.73$ for all varieties). Additionally, the latter phase was also correlated with harvest for Aragonez, Castelão and Fernão Pires ($r \geq 0.50$), whereas no significant correlations were found between budburst and harvest. Interestingly, the spring (a critical period as discussed in the next section) of 2011 was clearly the warmest of the study period (Figure 2), promoting the shortest flowering-véraison followed by the longest véraison-harvest interphases (indicating less suitable conditions) for Chasselas. However, intervals between phenophases were not significantly correlated (not shown), revealing that, for example, a shorter (longer) budburst-flowering period does not necessarily imply a shorter (extended) flowering-véraison period. These results are in agreement with previous studies (Jones and Davis, 2000b; Bock *et al.*, 2011; Tomasi *et al.*, 2011).

3. Temperature and phenology: effects and trends

Close relationships between main phenophases and temperature of the preceding months were reported using a multivariate regression approach. Moreover, all variables were negatively correlated ($r < 0$, not shown), meaning that increased temperatures during the selected months anticipate a specific event. The stepwise method was used to select the most significant predictors (individual and combined maximum, minimum and mean temperatures) at monthly (and multi-monthly) timescales in 1990-2011 (Table 3). Combining the three temperatures increased the coefficient of determination in several cases, though the selected months were generally the same. In fact, the discrepancy in the selection of the combined climatic variables can be primarily explained by the stepwise methodology. As maximum and minimum temperatures (besides mean temperature) for a given month were highly correlated ($0.76 \leq r \leq 0.89$ for all months, except September with $r = 0.56$), this method automatically selects the variable with better statistical performance in order to avoid multi-collinearity and overfitting. Hence, after the selection of one of the three variables for a given month, the others for the same month are automatically excluded, regardless of the physiological responses. Therefore, the isolation of the predictor months is greatly important, though multiple variables should be tested (avoiding previous selection of variables) in a statistical analysis (Due *et al.*, 1993).

Table 2 - Pearson correlation coefficients between main phenophases of the four varieties in Dois Portos, Portugal (1990-2011).

		Budburst	Flowering	Véraison
Aragonez	Budburst			
	Flowering	0.45		
	Véraison	0.09	**0.77**	
	Harvest	-0.02	0.34	**0.50**
Castelão	Budburst			
	Flowering	**0.53**		
	Véraison	0.30	**0.80**	
	Harvest	0.32	**0.47**	**0.61**
Chasselas	Budburst			
	Flowering	**0.57**		
	Véraison	**0.44**	**0.73**	
	Harvest	0.11	**0.58**	0.29
Fernão Pires	Budburst			
	Flowering	**0.51**		
	Véraison	0.37	**0.77**	
	Harvest	-0.07	**0.45**	**0.55**

Values in bold are significant at $p < 0.05$

Average minimum temperatures of the two-month February-March period (Chasselas and Fernão Pires) or the three-month January-February-March period (Aragonez and Castelão) were the major variables controlling grapevine budburst for the studied varieties ($0.46 \leq R_{cv}^2 \leq 0.69$), with Aragonez presenting the lower response. Only the latter variety displayed a significant trend of +1.1 days/yr ($p = 0.002$, Table 1), indicating that this event has been delayed along the period of study (Figure 4). Nonetheless, the results need to be cautiously interpreted as the data series is shorter for Aragonez (18 years) and may be substantially influenced by anomalously high (or low) values (e.g., April 6, 2005). In fact, Petrie and Sadras (2008) highlighted similar time series constraint using a 1993-2006 period. Additionally, budburst is projected to occur later in a warmer area of Australia (Margaret River) in response to future warming (Webb *et al.*, 2007). The authors pointed out the insufficient winter chilling for breaking dormancy in the region for these projections. However, no significant temperature trends were found over the winter periods in our study (Figure 2), though short-term (e.g., daily) responses may not be totally expressed in monthly averages (Due *et al.*,

Table 3 - Summary of most significant and not inter-correlated (99% confidence level) monthly (or multi-monthly) temperature variables (TX, TN and TG combined and analysed separately) and corresponding coefficients of determination after cross-validation (Rcv^2) for key phenophases of the four varieties in Dois Portos, Portugal (1990-2011).

	Budburst		Flowering		Véraison		Harvest	
	Regressor	R_{cv}^2	Regressor	R_{cv}^2	Regressor	R_{cv}^2	Regressor	R_{cv}^2
TX, TN and TG as variables								
Aragonez	TN$_{\text{Jan-Feb-Mar}}$	0.46	TX$_{\text{Mar-Apr}}$	0.75	TG$_{\text{Mar-Apr}}$	0.57	*nd*	
Castelão	TN$_{\text{Jan-Feb-Mar}}$	0.69	TX$_{\text{Mar-Apr}}$	0.78	TG$_{\text{Mar-Apr}}$ TN$_{\text{Jun}}$ TX$_{\text{Jul}}$	0.87	TX$_{\text{Apr}}$ TN$_{\text{Jun}}$ TX$_{\text{Sep}}$	0.63
Chasselas	TN$_{\text{Feb-Mar}}$	0.60	TG$_{\text{Mar-Apr}}$ TN$_{\text{Apr}}$	0.84	TN$_{\text{Mar-Apr}}$ TN$_{\text{Jul}}$	0.57	TG$_{\text{Mar-Apr}}$ TN$_{\text{Aug}}$	0.61
Fernão Pires	TN$_{\text{Feb-Mar}}$	0.63	TX$_{\text{Mar-Apr}}$	0.79	TN$_{\text{Mar-Apr}}$ TN$_{\text{Jul}}$	0.68	TX$_{\text{Mar}}$ TX$_{\text{Apr}}$ TX$_{\text{Jun}}$ TX$_{\text{Aug}}$	0.77
TX as variable								
Aragonez	TX$_{\text{Jan-Feb-Mar}}$	0.29	TX$_{\text{Mar-Apr}}$	0.75	TX$_{\text{Mar-Apr}}$	0.56	*nd*	
Castelão	TX$_{\text{Jan-Feb-Mar}}$	0.41	TX$_{\text{Mar-Apr}}$	0.78	TX$_{\text{Mar-Apr}}$ TX$_{\text{Jun}}$ TX$_{\text{Jul}}$	0.84	TX$_{\text{Mar}}$ TX$_{\text{Apr}}$ TX$_{\text{Jun}}$	0.51
Chasselas	TX$_{\text{Feb-Mar}}$	0.33	TX$_{\text{Mar-Apr}}$	0.77	TX$_{\text{Mar-Apr}}$	0.35	TX$_{\text{Apr}}$	0.32
Fernão Pires	TX$_{\text{Jan-Feb-Mar}}$	0.45	TX$_{\text{Mar-Apr}}$	0.79	TX$_{\text{Mar-Apr}}$	0.50	TX$_{\text{Mar}}$ TX$_{\text{Apr}}$ TX$_{\text{Jun}}$ TX$_{\text{Aug}}$	0.77
TN as variable								
Aragonez	TN$_{\text{Jan-Feb-Mar}}$	0.46	TN$_{\text{Mar-Apr}}$	0.52	TN$_{\text{Mar-Apr}}$	0.48	*nd*	
Castelão	TN$_{\text{Jan-Feb-Mar}}$	0.69	TN$_{\text{Mar-Apr}}$	0.54	TN$_{\text{Mar-Apr}}$	0.63	TN$_{\text{Mar-Apr}}$ TN$_{\text{Jun}}$	0.34
Chasselas	TN$_{\text{Feb-Mar}}$	0.60	TN$_{\text{Mar-Apr}}$	0.67	TN$_{\text{Mar-Apr}}$ TN$_{\text{Jul}}$	0.57	TN$_{\text{Mar-Apr}}$ TN$_{\text{Aug}}$	0.56
Fernão Pires	TN$_{\text{Feb-Mar}}$	0.63	TN$_{\text{Mar-Apr}}$	0.60	TN$_{\text{Mar-Apr}}$ TN$_{\text{Jul}}$	0.68	TN$_{\text{Apr}}$ TN$_{\text{Jun}}$	0.53
TG as variable								
Aragonez	TG$_{\text{Jan-Feb-Mar}}$	0.43	TG$_{\text{Mar-Apr}}$	0.74	TG$_{\text{Mar-Apr}}$	0.57	*nd*	
Castelão	TG$_{\text{Jan-Feb-Mar}}$	0.62	TG$_{\text{Mar-Apr}}$	0.75	TG$_{\text{Mar-Apr}}$ TG$_{\text{Jun}}$ TG$_{\text{Jul}}$	0.86	TG$_{\text{Mar-Apr}}$ TG$_{\text{Jun}}$	0.52
Chasselas	TG$_{\text{Feb-Mar}}$	0.47	TG$_{\text{Mar-Apr}}$ TG$_{\text{Apr}}$	0.82	TG$_{\text{Mar-Apr}}$	0.44	TG$_{\text{Mar-Apr}}$ TG$_{\text{Aug}}$	0.58
Fernão Pires	TG$_{\text{Jan-Feb-Mar}}$	0.61	TG$_{\text{Mar-Apr}}$	0.78	TG$_{\text{Mar-Apr}}$	0.59	TG$_{\text{Apr}}$ TG$_{\text{Jun}}$ TG$_{\text{Aug}}$	0.70

TX, TN and TG: maximum, minimum and mean temperatures, respectively; *nd*: not determined. Note that all temperatures are negatively correlated with phenophase dates.

1993). Practices such as pruning should not have a determinant impact on that response, as it was performed in similar time periods of each year (early January). On the other hand, other factors, such as soil temperature, soil water availability (precipitation effect) and starch content in the roots should influence this stage (Jackson and Lombard, 1993 ; Lavee and May, 1997 ; Keller, 2010). These results highlight the importance of developing phenological models (Chuine *et al.*, 2003 ; Parker *et al.*, 2011) quantifying the precise base temperatures and thermal requirements (defining varietal suitability), which may vary with variety and location (Oliveira, 1998 ; Garcia de Cortázar-Atauri *et al.*, 2009). As an illustration, calculated (budburst) threshold temperature may vary from 5.1 to 6.9ºC for Müller-Thurgau in cool winter climates (Nendel, 2010). Conversely (and similarly to our results in three varieties), no significant budburst trends were described for a long-term (1964-2009) dataset of eighteen varieties in the Veneto region, Italy (Tomasi *et al.*, 2011) and in Lower Franconia, Germany (Bock *et al.*, 2011), whereas earlier budburst were reported in Alsace (Duchêne and Schneider,

2005) and Burgundy (Jones *et al.*, 2005), France, as a result of temperatures rise.

Flowering timing also showed to be mostly influenced by March temperature, but now combined with April (preceding two-month period). Regarding the analysis of the combined three climatic variables, maximum March-April temperature was chosen for all the varieties except Chasselas, for which mean March-April and minimum April temperatures were selected. The model explained 75-84 % of the total variance of this event, which was generally the highest significance. The effect of springtime thermal conditions was particularly clear in the advanced flowering of 2007 (outlier for all varieties) as described above. Other studies (Jones and Davis, 2000b; Bock *et al.*, 2011; Tomasi *et al.*, 2011) have reported that both flowering and budburst are mainly controlled by (maximum) March and April temperatures. The former result may be ascribed to the warmer climate conditions within the LWR (and then earlier budburst) compared with the above studies (e.g., Germany). Moreover, strong linear relationships between flowering dates and spring temperatures were also found for other plant species (Menzel *et al.*, 2005).

Véraison was still mainly driven by March and April temperatures ($0.57 \leq R_{cv}^2 \leq 0.87$ for the combined analysis), which is consistent with the strong correlation between flowering and véraison onsets detailed above. Another determinant variable was late monthly temperature (e.g., July). Once again, April temperatures were crucial for harvest, though preceding months/variables were also selected ($0.61 \leq R_{cv}^2 \leq 0.77$ for the combined analysis), suggesting the increased influence of cultural practices over the season. However, no significant predictors could be isolated for the harvest of Aragonez, due to its smaller sample size (17 years). Therefore, the strong link between winegrape phenology and springtime thermal conditions as well as the increased influence of viticultural practices (non-climatic drivers) during maturity are determinant in the LWR, as in other regions (Jones and Davis, 2000b; Duchêne and Schneider, 2005; Webb *et al.*, 2007; Petrie and Sadras, 2008; Bock *et al.*, 2011; Tomasi *et al.*, 2011).

Significant positive trends in temperatures were found for the spring period (Figure 2). However, no significant trends were observed for flowering, véraison and harvest onsets, with the exception of Fernão Pires, where anticipation in harvest (negative trend) of roughly -1.0 days/yr was depicted ($p \leq 0.001$, Table 1). This result may be ascribed to a higher climatic sensitivity over maturation, which was also exposed in interphase trends (as described below). Indeed, based on acid and sugar levels over a 45-year period, Jones and Davis (2000b) concluded that Merlot is a more phenologically and climatically sensitive winegrape variety compared with Cabernet Sauvignon in Bordeaux, France.

Additionally, negative trends (shortest interval) in the time series were mostly found for interphases: flowering to véraison (Aragonez and Castelão), véraison to harvest (Fernão Pires) and budburst to harvest (Aragonez, Chasselas and Fernão Pires) (Table 1), which are generally linked to better climatic conditions for growth and development (Jones and Davis, 2000b). However, in warmer Portuguese regions, harvest dates may be brought forward into a warmer period of the year, with detrimental effects on yield and quality (Jones, 2006; Duchêne *et al.*, 2010; Santos *et al.*, 2011).

The significance of the apparent discrepancy in slopes between dates of events and intervals in phenology may be attributed to the accumulated thermal effect along the season (Tomasi *et al.*, 2011), which cannot be clearly disclosed by the date of each phenophase. Though generally not statistically significant, all seasonal (and yearly) mean temperatures displayed positive slopes (not shown). Furthermore, a persistent effect of spring (near budburst) temperatures was also reported to influence the vegetative growth of Cabernet Sauvignon grapevines in Washington, USA (Keller and Tarara, 2010). Other studies (Jones and Davis, 2000b; Duchêne and Schneider, 2005; Bock *et al.*, 2011; Tomasi *et al.*, 2011; Neethling *et al.*, 2012; Webb *et al.*, 2012) showed significant phenological shifts, particularly for the last events (véraison and harvest) and intervals (e.g., budburst to harvest). However, these authors generally reported lower rates (e.g., roughly -0.3 days/yr for the budburst-harvest interval in Germany and northern Italy), which may be attributed to the different temporal windows and lengths used for the trend assessments in the different studies. In fact, Webb *et al.* (2012) computed significant higher trends in maturity (e.g., -1.25 days/yr for Shiraz in Central Victoria, Australia), when a shorter and common period in their study (1985-2009) was defined. In the same country, Sadras and Petrie (2011) concluded that the early maturity of Chardonnay, Shiraz and Cabernet Sauvignon varieties was mostly related to early onset (86 % of the variation in maturity) rather than faster ripening in response to warming. Moreover, increases in potential alcohol level at harvest were reported during the last decades in Alsace (Duchêne and Schneider, 2005).

It is worthwhile noting that, contrary to usual wine production practices (e.g., harvest dates are varietal and oenological dependent), the trends in maturity were assessed by a biophysical parameter (potential alcohol content) similar to all varieties, which diminishes the effect of non-climatic drivers (Webb *et al.*, 2011, 2012). Nevertheless, the period between budburst and véraison was also determined in order to disregard the harvest date. Non-significant trends were displayed in the former interval for the white varieties (Chasselas and Fernão Pires), indicating the major influence of the later phase (i.e., harvest) (Table 1). Conversely, for the red varieties, which are commonly more heat demanding, significant trends were found between budburst and véraison (e.g., -1.5 days/yr for Aragonez), revealing that effects may occur at earlier periods (flowering to véraison) of the cycle (Table 1).

CONCLUSIONS

This study presents the first analysis of the temporal trends in winegrape phenology and corresponding connections to temperature in a major Portuguese wine region. Our results highlight the key role played by springtime thermal conditions in phenology, particularly in flowering, which in turn influence the following phases, though non-climate drivers (e.g., viticultural practices) are also important during ripening. While only a few trends were found for phenophases, several significant negative slopes were displayed for interphases, which was a reflection of the accumulated thermal effects along the seasons. This issue is especially relevant under a scenario of projected future warmer climates (where these relationships may be changed), although this assessment is out of the scope of the present study. As a result, phenological shifts may occur in the long term, emphasizing the need to assess varietal characteristics and responses to climate at regional level. Despite the considerable lack of relatively long time series of phenological data for the Portuguese wine regions, further analysis on the impacts of climate change in winegrape phenology is currently underway, which may provide crucial information on the development and suitability of grapevine varieties, determining viticultural practices and winegrower's income.

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REFERENCES

Bock A., Sparks T., Estrella N. and Menzel A., 2011. Changes in the phenology and composition of wine from Franconia, Germany. *Clim. Res.*, **50**, 69-81.

Caffarra A. and Eccel E., 2011. Projecting the impacts of climate change on the phenology of grapevine in a mountain area. *Aust. J. Grape Wine Res.*, **17**, 52-61.

Chuine I., Kramer K. and Hänninen H., 2003. Plant development models. In: *Phenology - An Integrative Environmental Science (Tasks for Vegetation Science 39)*. Schwartz M.D. (Ed.), Kluwer Academic Publishers, pp. 217-235.

Duchêne E. and Schneider C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. *Agron. Sustain. Dev.*, **25**, 93-99.

Duchêne E., Huard F., Dumas V., Schneider C. and Merdinoglu D., 2010. The challenge of adapting grapevine varieties to climate change. *Clim. Res.*, **41**, 193-204.

Due G., Morris M., Pattison S. and Coombe B.G., 1993. Modelling grapevine phenology against weather: considerations based on a large data set. *Agric. Forest Meteorol.*, **65**, 91-106.

FAO, 2006. *World Reference Base for Soil Resources 2006, a Framework for International Classification, Correlation and Communication*. World soil resources reports 103, Food and Agriculture Organization of the United Nations, Rome.

Ferreira M.I., Silvestre J., Conceição N. and Malheiro A.C., 2012. Crop and stress coefficients in rainfed and deficit irrigation vineyards using sap flow techniques. *Irrig. Sci.*, **30**, 433-447.

Fraga H., Santos J.A., Malheiro A.C. and Moutinho-Pereira J., 2012. Climate change projections for the Portuguese viticulture using a multi-model ensemble. *Ciência Téc. Vitiv.*, **27**, 39-48.

Fraga H., Malheiro A.C., Moutinho-Pereira J., Jones G.V., Alves F., Pinto J.G. and Santos J.A., 2013a. Very high resolution bioclimatic zoning of Portuguese wine regions: present and future scenarios. *Reg. Environ. Change*, doi: 10.1007/s10113-013-0490-y.

Fraga H., Malheiro A.C., Moutinho-Pereira J. and Santos J.A., 2013b. Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties. *Int. J. Biometeorol.*, **57**, 909-925.

Garcia de Cortázar-Atauri I., Brisson N. and Gaudillère J.P., 2009. Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). *Int. J. Biometeorol.*, **53**, 317-326.

García-Mozo H., Mestre A. and Galán C., 2010. Phenological trends in southern Spain: a response to climate change. *Agric. Forest Meteorol.*, **150**, 575-580.

Grifoni D., Mancini M., Maracchi G., Orlandini S. and Zipoli G., 2006. Analysis of Italian wine quality using freely available meteorological information. *Am. J. Enol. Vitic.*, **57**, 339-346.

Hijmans R.J., Cameron S.E., Parra J.L., Jones P.G. and Jarvis A., 2005. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.*, **25**, 1965-1978.

IVV, 2011. *Vinhos e Aguardentes de Portugal, Anuário 2010/11*. Ministério da Agricultura, do Desenvolvimento Rural e das Pescas : Instituto da Vinha e do Vinho, Lisboa.

Jackson D.I. and Lombard P.B., 1993. Environmental and management practices affecting grape composition and wine quality – a review. *Am. J. Enol. Vitic.*, **44**, 409-430.

Jones G.V. and Davis R.E., 2000a. Using a synoptic climatological approach to understand climate-viticulture relationships. *Int. J. Climatol.*, **20**, 813-837.

Jones G.V. and Davis R.E., 2000b. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *Am. J. Enol. Vitic.*, **51**, 249-261.

Jones G.V., 2003. Winegrape phenology. In : *Phenology - An Integrative Environmental Science (Tasks for Vegetation Science 39)*. Schwartz M.D. (Ed.), Kluwer Academic Publishers, pp. 523-539.

Jones G.V., Duchêne E., Tomasi D., Yuste J., Braslavska O., Schultz H.-R., Martinez C., Boso S., Langellier F., Perruchot C. and Guimberteau G., 2005. Changes in European winegrape phenology and relationships with climate. In : *XIVth International GESCO Viticulture Congress*, Geisenheim (Germany), pp. 55-61.

Jones G.V., 2006. Climate and terroir : impacts of climate variability and change on wine. In : *Fine Wine and Terroir - The Geoscience Perspective*. Macqueen R.W. and Meinert L.D. (Eds.), Geoscience Canada Reprint Series Number 9, Geological Association of Canada, St. John's, Newfoundland, pp. 1-14.

Keller M., 2010. Managing grapevines to optimise fruit development in a challenging environment : a climate change primer for viticulturists. *Aust. J. Grape Wine Res.*, **16**, 56-69.

Keller M. and Tarara J.M., 2010. Warm spring temperatures induce persistent season-long changes in shoot development in grapevines. *Ann. Bot.*, **106**, 131-141.

Kottek M., Grieser J., Beck C., Rudolf B. and Rubel F., 2006. World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z. (Berl.)*, **15**, 259-263.

Lavee S. and May P., 1997. Dormancy of grapevine buds – facts and speculation. *Aust. J. Grape Wine Res.*, **3**, 31-46.

Lopes J., Eiras-Dias J.E., Abreu F., Clímaco P., Cunha J.P. and Silvestre J., 2008. Exigências térmicas, duração e precocidade de estados fenológicos de castas da colecção ampelográfica nacional. *Ciência Téc. Vitiv.*, **23**, 61-71.

Lorenz D.H., Eichhorn K.W., Bleiholder H., Klose R., Meier U. and Weber E., 1995. Growth stages of the grapevine : phenological growth stages of the grapevine (*Vitis vinifera* L. ssp. *vinifera*) - Codes and descriptions according to the extended BBCH scale. *Aust. J. Grape Wine Res.*, **1**, 100-103.

Magalhães N.P., 2008. *Tratado de Viticultura - A Videira, a Vinha e o "Terroir"*. Chaves Ferreira Publicações, Lisboa, Portugal.

Malheiro A.C., Santos J.A., Fraga H. and Pinto J.G., 2010. Climate change scenarios applied to viticultural zoning in Europe. *Clim. Res.*, **43**, 163-177.

Marta A.D., Grifoni D., Mancini M., Storchi P., Zipoli G. and Orlandini S., 2010. Analysis of the relationships between climate variability and grapevine phenology in the Nobile di Montepulciano wine production area. *J. Agric. Sci.*, **148**, 657-666.

McCarthy M.G., 1999. Weight loss from ripening berries of Shiraz grapevines (*Vitis vinifera* L. cv. Shiraz). *Aust. J. Grape Wine Res.*, **5**, 10-16.

Menzel A., Estrella N. and Testka A., 2005. Temperature response rates from long-term phenological records. *Clim. Res.*, **30**, 21-28.

Neethling E., Barbeau G., Bonnefoy C. and Quenol H., 2012. Change in climate and berry composition for grapevine varieties cultivated in the Loire Valley. *Clim. Res.*, **53**, 89-101.

Nendel C., 2010. Grapevine bud break prediction for cool winter climates. *Int. J. Biometeorol.*, **54**, 231-241.

Oliveira M., 1998. Calculation of budbreak and flowering base temperatures for *Vitis vinifera* cv. Touriga Francesa in the Douro Region of Portugal. *Am. J. Enol. Vitic.*, **49**, 74-78.

Parker A.K., Garcia de Cortazar Atauri I., van Leeuwen C. and Chuine I., 2011. General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Aust. J. Grape Wine Res.*, **17**, 206-216.

Petrie P.R. and Sadras V.O., 2008. Advancement of grapevine maturity in Australia between 1993 and 2006: putative causes, magnitude of trends and viticultural consequences. *Aust. J. Grape Wine Res.*, **14**, 33-45.

Sadras V.O. and Petrie P.R., 2011. Climate shifts in south-eastern Australia : early maturity of Chardonnay, Shiraz and Cabernet Sauvignon is associated with early onset rather than faster ripening. *Aust. J. Grape Wine Res.*, **17**, 199-205.

Santos J.A., Malheiro A.C., Karremann M.K. and Pinto J.G., 2011. Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. *Int. J. Biometeorol.*, **55**, 119-131.

Santos J.A., Malheiro A.C., Pinto J.G. and Jones G.V., 2012. Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. *Clim. Res.*, **51**, 89-103.

Santos J.A., Grätsch S.D., Karremann M.K., Jones G.V. and Pinto J.G., 2013. Ensemble projections for wine production in the Douro Valley of Portugal. *Clim. Change*, **117**, 211-225.

Tomasi D., Jones G.V., Giust M., Lovat L. and Gaiotti F., 2011. Grapevine phenology and climate change: relationships and trends in the Veneto Region of Italy for 1964-2009. *Am. J. Enol. Vitic.*, **62**, 329-339.

Urhausen S., Brienen S., Kapala A. and Simmer C., 2011. Climatic conditions and their impact on viticulture in the Upper Moselle region. *Clim. Change*, **109**, 349-373.

Webb L.B., Whetton P.H. and Barlow E.W.R., 2007. Modelled impact of future climate change on the phenology of winegrapes in Australia. *Aust. J. Grape Wine Res.*, **13**, 165-175.

Webb L.B., Whetton P.H. and Barlow E.W.R., 2011. Observed trends in winegrape maturity in Australia. *Glob. Change Biol.*, **17**, 2707-2719.

Webb L.B., Whetton P.H., Bhend J., Darbyshire R., Briggs P.R. and Barlow E.W.R., 2012. Earlier wine-grape ripening driven by climatic warming and drying and management practices. *Nat. Clim. Change*, **2**, 259-264.

Winkler A.J., Cook J.A., Kliewer W.M. and Lider L.A., 1974. *General Viticulture*. University of California Press, USA.