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Predicting the flowering date of Portuguese grapevine varieties using temperature-based phenological models: a multi-site approach

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Abstract

Phenological models for predicting the grapevine flowering were tested using phenological data of 15 grape varieties collected between 1990 and 2014 in Vinhos Verdes and Lisbon Portuguese wine regions. Three models were tested: Spring Warming (Growing Degree Days – GDD model), Spring Warming modified using a triangular function – GDD triangular and UniFORC model, which considers an exponential response curve to temperature. Model estimation was performed using data on two grape varieties (Loureiro and Fernão Pires), present in both regions. Three dates were tested for the beginning of heat unit accumulation (t_0 date): budburst, 1 January and 1 September. The best overall date was budburst. Furthermore, for each model parameter, an intermediate range of values common for the studied regions was estimated and further optimized to obtain one model that could be used for a diverse range of grape varieties in both wine regions. External validation was performed using an independent data set from 13 grape varieties (seven red and six white), different from the two used in the estimation step. The results showed a high coefficient of determination (R^2: 0.59–0.89), low Root Mean Square Error (RMSE: 3–7 days) and Mean Absolute Deviation (MAD: 2–6 days) between predicted and observed values. The UniFORC model overall performed slightly better than the two GDD models, presenting higher R^2 (0.75) and lower RMSE (4.55) and MAD (3.60). The developed phenological models presented good accuracy when applied to several varieties in different regions and can be used as a predictor tool of flowering date in Portugal.

Introduction

The study of typical vegetation cycles and their connection to climate, called vegetation phenology, plays a prominent role in local, regional and global agricultural and ecosystem simulation models (Running and Hunt, 1993; Chuine, 2000; Jones, 2003). The knowledge of the annual timing of phenophases and their variability can help decision-making in crop management, which leads finally to higher and more stable crop yields and quality as well as to improved food quality (Chmielewski *et al.*, 2013). Phenology monitoring and forecasting is an important support tool for the implementation of cropping schedules, the organization of crop rotation and catch cropping (Chmielewski *et al.*, 2013). It is also important to support crop management operations such as irrigation, fertilization and crop protection (Ruml and Vulić, 2005). Phenological observations are also useful to define the growing season length, evaluate the risk of frost damage and to make forecasts of plant development and harvest dates (Chmielewski *et al.*, 2013).

In viticulture, phenological modelling is important for a variety of applications, such as the more efficient planning of harvest and viticultural practices (Williams *et al.*, 1985), predicting vulnerability to pest attacks and the selection of cultivars in new areas (Gladstones, 1992; Bindi *et al.*, 1997; Orlandini and Mancini, 1999; Jarvis *et al.*, 2017). The models can be coupled with climate change scenarios projecting the impact of climate change on grapevine (Cola *et al.*, 2017). However, the difficulties in obtaining phenological models that provide accurate predictions on a local and regional scale prevent them from being exploited to their full potential (Caffarra and Eccel, 2010).

Phenology modelling requires four essential steps: data collection, model definition, adjustments of the model to the data using an adapted optimization algorithm that ensures correct

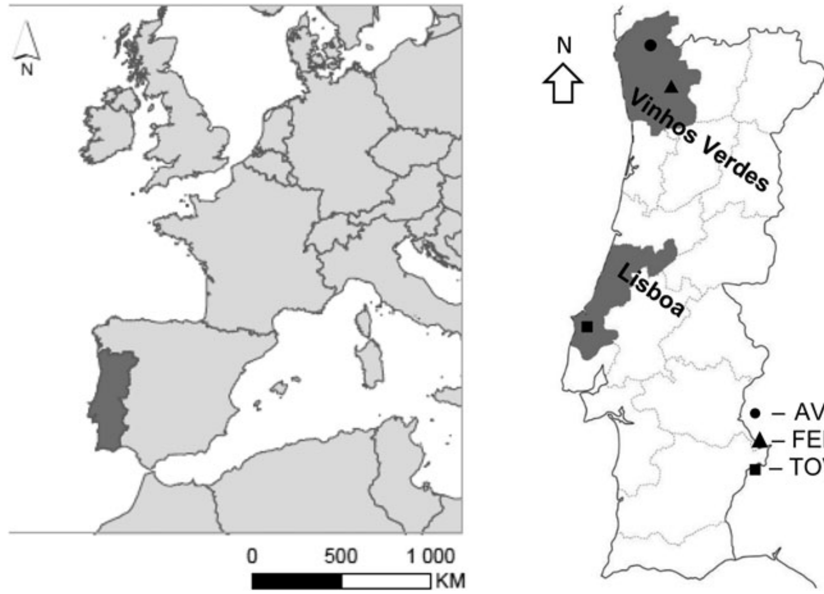


Fig. 1. Map of Portugal with the studied wine regions represented and location of the sites analysed in this work.

convergence and tests of the model hypotheses (Chuine *et al*., 1999). Data collection includes observations of meteorological parameters, with the environmental temperature being the variable most commonly used, photoperiod and phenological stages. Phenological data can be derived from remote sensing images (Cunha *et al*., 2010), or airborne pollen (Cunha *et al*., 2015), but the observations in phenological collections are still the most reliable data mainly for grapevine studies.

Based on the BBCH *(Biologische Bundesanstalt, Bundessortenambt und Chemische Industrie)* scale for *Vitis vinifera* L., the vegetative cycle begins at budburst (07) and finishes at leaf colouring (92) and fall (95) at the end of the growth phase, when the development of the plant ceases and the dormancy stage (00) begins (Pouget, 1972; Meier, 2001; Chaos *et al*., 2007). Temperature and photoperiod are fundamental in influencing grapevine phenological dynamics (Winkler *et al*., 1974; Huglin, 1978; Jones and Davis, 2000; Duchene and Schneider, 2005; Jones *et al*., 2005; van Leeuwen *et al*., 2008; Zapata *et al*., 2015). Temperature affects cell metabolism, carbon accumulation and other biochemical processes (Tanino *et al*., 2010). The variation in photoperiod, including long nights, affects the phytochromes (photoreceptors), which control signal transduction in order to regulate shoot growth (Chaos *et al*., 2007; Olsen, 2010; Tanino *et al*., 2010; Victor *et al*., 2010). Although grapevine phenology is therefore correlated with local conditions and genetics (varietal choice) (Gladstones, 1992; van Leeuwen *et al*., 2004; 2008), it has been shown that temperature is the predominant influence on development over photoperiod and light intensity (Buttrose, 1969). In fact, photoperiod is unlikely to influence inter-annual variation of phenology in a single place since it does not vary from one year to another (Chuine *et al*., 1999).

Understanding how temperature influences the timing of grapevine vegetative and reproductive development and identifying varietal specific differences in phenology is fundamental. In fact, when these developmental phases are well-adapted to the local conditions, the grapes at harvest may acquire a desirable combination of parameters such as sugar, acidity, aromatic and phenolic compounds or other qualities to produce wine with high quality (Jones and Davis, 2000; Jones *et al*., 2005; Jones, 2006; van Leeuwen *et al*., 2008). Furthermore, phenological models, coupled with climate scenarios, could play an important role in predicting the triggering of grapevine phenological stages that could help avoid stress and mitigate projected changes in climate (Cunha and Richter, 2016).

Different phenological models for predicting the dates of flowering have been described in the literature (Chuine *et al*., 2003; Parker *et al*., 2011). Some models examine only the effect of temperature during the active growth period (forcing temperature) such as the Thermal Time model (Cannell and Smith, 1983) also known as the Spring Warming model (Hunter and Lechowicz, 1992). Other modelling approaches include the influence of chilling temperatures such as the Alternating model (Murray *et al*., 1989), the Parallel model (Landsberg, 1974; Hänninen, 1990; Kramer, 1994), the Sequential model (Sarvas, 1974; Hänninen, 1990; Kramer, 1994) and the Unified model (Chuine, 2000). In phenological modelling, the development of site-specific models is important because plants are adapted to the surrounding environment and differences in the timing of phenological development are observed (Caffarra and Eccel, 2010; Parker *et al*., 2011; 2013; Ruml *et al*., 2016). Therefore, the information derived from these site-specific models contributes to understanding the plasticity of a species or of varieties within the same species to regions with different climatic conditions. In addition, site-specific models are a useful tool to help winemakers in the management of practices in the vineyard, especially at the flowering date since this is a good indicator of harvest date. Nonetheless, it is also important to develop a unified model of the multi-regional application to describe and predict phenological behaviour on a spatial scale (Parker *et al*., 2011).

Therefore, the main objective of the current study was to test and validate multi-year, multi-variety and multi-site temperature-based phenological models of flowering date using data collected in Portugal, the most western viticulture zone of Europe.

The phenological models were calibrated using data on two grape varieties (Loureiro and Fernão Pires) and externally validated using an independent data set from 13 grape varieties collected in two Portuguese wine regions and contains a large number of autochthonous varieties concentrated in a small area. The best models were chosen in terms of efficiency relative to

Table 1. Summary of average, minimum and maximum temperatures for each studied region for the period from 1 January to the budburst date, from 1 January date to the flowering date and from budburst to flowering from 1990 to 2014

	1 January – Budburst (07)	1 January – Flowering (65)	Budburst-Flowering	Growing season
Temperature (°C)	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Arcos de Valdevez (AVV)				
Mean	10 ± 2.8	12 ± 3.5	14 ± 3.2	16.6 ± 0.78
Minimum	6 ± 3.3	8 ± 3.4	9 ± 2.8	11.6 ± 0.63
Maximum	15 ± 3.5	16 ± 4.4	19 ± 4.3	22 ± 1.1
Torres Vedras (TOV)				
Mean	13 ± 2.4	15 ± 3.1	17 ± 2.6	19.3 ± 0.90
Minimum	10 ± 2.6	11 ± 2.9	13 ± 2.2	15.1 ± 0.61
Maximum	16 ± 2.7	18 ± 3.8	20 ± 3.6	23 ± 1.2
Felgueiras (FEL)				
Mean	12 ± 2.9	13 ± 3.3	15 ± 2.9	16.6 ± 0.78
Minimum	8 ± 3.4	9 ± 3.6	11 ± 2.9	11.6 ± 0.63
Maximum	16 ± 3.3	17 ± 3.8	19 ± 3.7	22 ± 1.1

SD, standard deviation.

complexity. The developed models were intended to convey temporal and spatial robustness for the species *Vitis vinifera* L. in Portugal.

Materials and methods

Study area

The research was carried out in two Portuguese wine regions: Vinhos Verdes and Lisbon (Fig. 1). The phenological data set in the Vinhos Verdes region was collected at two test sites, one located in Arcos de Valdevez (AVV) in the experimental field of the Amândio Galhano Wine Station research (41°48′′57′N, 8° 25′35′W, 70 m a.s.l) and the second in Felgueiras (FEL) in the Quinta de Sergude Experimental Station of Fruticulture (41° 16′N 8°05′W, 110 m a.s.l.), located about 50 km south of the AVV test site. In the Lisbon wine region, the phenological data set was collected at Quinta dos Almoínha (39°01′46′′N, 9° 01′35′′W, 99 m a.s.l) belonging to the Portuguese 'Instituto Nacional de Investigação Agrária e Veterinária' located in Dois Portos, Torres Vedras (TOV).

The wine regions studied differ greatly in terms of weather, soils, grape varieties and vine-growing systems. In both wine regions, the most significant climatic feature is an irregular annual rainfall level distributed throughout the year, mainly concentrated in winter and spring. Air temperature increases inversely to precipitation: winters are cool and wet, and summers are hot and dry (Cunha *et al*., 2015).

Temperature and phenological observations

The meteorological data were recorded in weather stations located near the field (<5 km) used for the phenological observations. Daily observations of maximum and minimum temperatures were used to calculate the daily mean temperature (T_m, °C). Annual mean temperatures are typically about 15 and 17 °C in the Vinhos Verdes and Lisbon regions, respectively. The TOV experienced warmer temperatures (mean, minimum and maximum) for the period from 1 January to flowering (Table 1), while AVV registered lower temperatures during this period. In TOV, the mean temperature during the period between budburst (07) and flowering (65) was about 2.3 °C higher than the mean temperature in the same period in AVV and 1.6 °C in FEL (Table 1).

During the growing season the average temperature is about 17 °C in AVV and 20 °C in TOV, and according to the climate maturity grouping (Jones, 2006), the growing season can be classified as 'Intermediate' and 'Warm', respectively, for AVV and TOV wine regions (Table 1).

The current study is based on long-term grapevine phenological observations for the dates of budburst (07) and flowering (65) collected in each region. Time-series were collected between 1990 and 2014 (periods ranged between 8 and 25 years, according to the region) for 15 different grape varieties (eight white and seven red) (Table 2). Phenological observations were collected, at field levels per grape variety every 3–4 days in AVV and TOV and 6–7 days in FEL. Phenological observations were registered according to the 'Organisation Internationale de la Vigne et du Vin' (OIV) phenophase descriptors (OIV, 2009). A given phenological stage was reached, and date recorded, when the event occurred in 50% of the plants for each grape variety, at the stages 'C: budbreak' and 'I: flowering' of the Baggiolini phenological scale, which corresponds to the stages 'EL 07 Beginning of bud burst: green shoot tips just visible' and 'EL 65 Full flowering: 50% of flowerhoods fallen' respectively according to the Eichhorn and Lorenz (E–L) system (Lorenz *et al*., 1995).

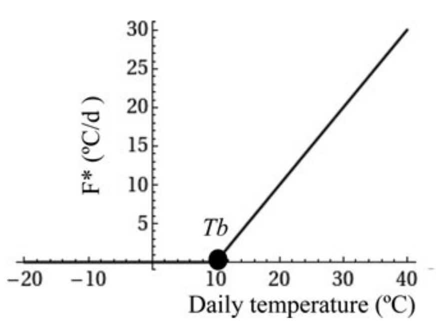
Modelling grapevine phenology

In the current work, different phenological models were tested and validated for predicting grapevine flowering dates at the variety level. Several long-term series of phenological data of different grapevine varieties were collected in Portuguese wine regions (Vinhos Verdes and Lisbon) and used in the development of the models. The varieties were compared within the same

Table 2. Average and standard deviation of the budburst and flowering dates for the grape varieties studied and the period between these two phenological stages (Budburst-Flowering)

Variety	Years (no)				Budburst (07)	Flowering (65)	Budburst-Flowering
	AVV	TOV	FEL	Total	DOY	DOY	No of days
White varieties							
Alvarinho	25	20	–	45	80 ± 7.0	146 ± 8.7	66 ± 8.3
Avesso	8	–	–	8	77 ± 4.9	144 ± 8.6	67 ± 7.2
Azal	8	–	–	8	86 ± 5.9	151 ± 8.5	65 ± 8.4
Chasselas	8	25	–	33	76 ± 8.5	143 ± 8.8	67 ± 7.6
Fernão Pires	25	25	–	50	75 ± 7.3	144 ± 9.3	69 ± 8.3
Loureiro	25	20	15	60	84 ± 9.9	148 ± 9.4	64 ± 10.0
Pedernã	17	–	15	32	95 ± 12.1	154 ± 9.9	60 ± 11.6
Trajadura	25	–	15	40	94 ± 9.8	153 ± 9.4	60 ± 11.0
Red varieties							
Aragonez	–	21	–	21	81 ± 9.6	145 ± 8.8	64 ± 8.6
Baga	–	20	–	20	83 ± 8.0	145 ± 9.5	62 ± 7.4
Castelão	8	25	–	33	74 ± 8.3	141 ± 8.5	67 ± 7.6
Espadeiro tinto	25	–	14	39	94 ± 10.3	153 ± 9.4	59 ± 10.4
Padeiro Basto	25	14	–	39	89 ± 7.6	151 ± 7.5	62 ± 8.6
Touriga Nacional	–	20	–	20	77 ± 7.7	141 ± 9.8	64 ± 7.8
Vinhão	25	–	–	25	94 ± 6.8	154 ± 8.8	61 ± 9.7

The days of the year (DOY) presented for each period were calculated from 1 January (and this day was considered day 1).



$$R_f = GDD(x_t) = \begin{cases} 0 \; if \; x_t < Tb \\ x_t - Tb \; if \; x_t \geq Tb \end{cases} \quad (2)$$

Fig. 2. Graphic representation of the Growing Degree Days (GDD) approach. F^* is the number of forcing units, x_t is the daily mean temperature and T_b is the base temperature above which the thermal summation is calculated (the T_b of 10 °C is used as an example for model representation).

modelling framework and the models were applied to different locations in order to achieve a single model with fixed optimized parameters that could forecast multi-variety and multi-site grapevine flowering dates accurately.

The models were developed using the program PMP 5.5 (Phenology Modeling Platform) (Chuine *et al.*, 2003).

Phenological model

Three different phenological models were tested: Spring Warming (Growing Degree Days – GDD model), Spring Warming modified (designated GDD triangular) and UniFORC (Chuine *et al.*, 2003).

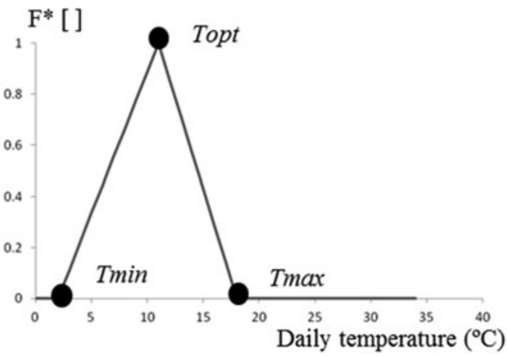
These models consider only the action of forcing temperatures and they assume that a given phenological stage occurs on the day (t_s) when a critical value of the state of forcing temperatures (S_f), denoted by F^* has been reached Eqn (1):

$$S_f(t_s) = \sum_{t_0}^{ts} Rf(x_t) \geq F^* \quad (1)$$

The S_f is described as a sum of the daily rate of forcing (R_f), which is a function of temperature (x_t is the daily mean temperature). In the current work, three models were used to estimate R_f.

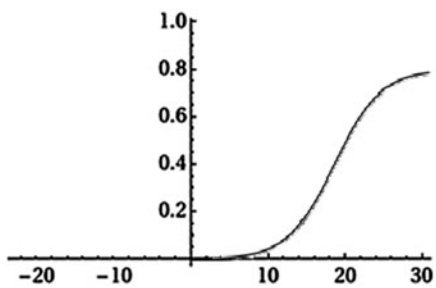
Growing Degree Day model

The GDD (°/day) approach (Fig. 2; Eqn (2)) includes three parameters, t_0, T_b and F^*, where T_b corresponds to a base temperature above which the number of forcing units is calculated (van der Schoot and Rinne, 2011).



$$R_f(x_t) = \begin{cases} 0 \; if \; x_t << Tmin \\ \frac{x_t - Tmin}{Topt - Tmin} \; if \; Tmin < x_t << Topt \\ \frac{x_t - Tmax}{Topt - Tmax} \; if \; Topt < x_t < Tmax \\ 0 \; if \; x_t >> Tmax \end{cases} \quad (3)$$

Fig. 3. Graphic representation of Growing Degree Days (GDD) model modified with the triangular function. F^* is the forcing units, x_t is the daily mean temperature, T_{min} is the minimum temperature above which the thermal summation is calculated, T_{opt} is the optimal temperature from which the amount of units of heat accumulated start to decrease and T_{max} is the maximum temperature from which no thermal summation occurs.



$$R_f(x_t) = \begin{cases} 0 \; if \; x_t < 0 \\ \frac{1}{1 + e^{d(x_t - e)}} \; if \; x_t \geq 0 \end{cases} \quad (4)$$

Fig. 4. Graphic representation of UniFORC model Eqn (4). F^* is forcing units, x_t is the daily mean temperature, d defines the sharpness of the response curve and e is the mid-response temperature.

Growing Degree Days Triangular model

The GDD triangular approach includes four model parameters to be estimated the t_0, T_{min}, T_{opt}, T_{max} and F^* (Fig. 3, Eqn (3)). This approach is based on ratios of temperatures, hence the F^* takes values between 0 and 1.

UniFORC model

The UniForc model includes four parameters t_0, d, e, F^* to be fitted, with $d < 0$ and $e > 0$ (Fig. 4, Eqn (4)). The parameter d (<0) defines the sharpness of the response curve and e (>0) is the mid-response temperature. The rate of forcing F^* is an exponential function that takes values between 0 and 1.

Model estimation

In the modelling strategy used in the current paper, the timing of flowering was estimated in a two-phase approach. The varieties with the longest time series in AVV (Fernão Pires, $n = 25$, and Loureiro, $n = 25$) and in TOV (Fernão Pires, $n = 25$) were used in this process.

In a first phase, estimation of the models was based on an iterative generalization process where three dates were tested for the beginning of the accumulation of heat units (t_0 date): budburst date, 1 January and 1 September. This allowed selection of the best overall t_0 date as well as an intermediate range of values for the estimated parameter common for the three regions.

In a second phase, the intermediate values of the estimated parameters were iteratively optimized (the T_b for the GDD model, the T_{min}, T_{opt} and T_{max} in GDD Triangular model and e in UniFORC model) for each model, in order to obtain one model with fixed parameters that can be used for estimation of the flowering time in a diverse range of grape varieties.

Model parameters were fitted using the Metropolis algorithm (Metropolis *et al.*, 1953), known to avoid local extrema of any kind of function while searching the solution for an optimization problem.

Model validation

To evaluate the prediction accuracy of the estimated models, an external validation was performed using an independent data set consisting of several time-series ranging from 8 to 25 years (398 observations), from 13 grape varieties (seven red and six white) in the three test sites (AVV, TOV and FEL) from two wine regions (Table 2). This allows selection of the most precise model to predict the timing of grapevine flowering based on an inter-regional assessment of the model accuracy.

Therefore, in agreement with the previous parameterization in the GDD model, the T_b was fixed and F^* was fitted; in the GDD Triangular model the T_{min}, T_{opt}, T_{max} value were fixed and the F^* was fitted; in the UniFORC model the value of e was fixed and the d and F^* were fitted.

Goodness-of-fit indicators

The estimation and selection of the best model during the validation process was based on the model fit by coefficient of determination (R^2, Eqn (2)), the Root Mean Square Error (RMSE, Eqn (3)) and on the Mean Absolute Deviation (MAD, Eqn(4)) between predicted and observed values calculated based on the

Table 3. Summary of the estimation process results for the three models studied

Date for accumulation of heat units (t_0)	Fernão Pires								Loureiro			
	AVV				TOV				AVV			
	R^2	RMSE	MAD	$>Q_{75}$	R^2	RMSE	MAD	$>Q_{75}$	R^2	RMSE	MAD	$>Q_{75}$
Growing Degree Days (GDD)												
1 January	0.81	4.2	3.49	6.88	0.74	4.3	3.49	6.98	0.70	4.7	3.95	7.73
1 September	0.82	4.2	3.54	6.63	0.74	4.3	3.50	6.95	0.71	4.7	3.86	7.73
Budburst	**0.87**	**3.1**	**2.56**	**4.97**	**0.71**	**4.0**	**3.38**	**6.58**	**0.80**	**4.1**	**3.24**	**6.72**
Growing Degree Days (GDD) Triangular												
1 January	0.82	4.2	3.52	6.67	0.75	4.2	3.39	7.17	0.70	4.8	3.96	8.00
1 September	0.82	4.1	3.37	6.75	0.74	4.3	3.54	7.18	0.70	4.7	3.83	7.90
Budburst	**0.87**	**3.1**	**2.49**	**4.95**	**0.72**	**3.9**	**3.28**	**6.23**	**0.80**	**4.1**	**3.23**	**6.67**
UniFORC												
1 January	0.82	4.1	3.41	6.38	0.65	5.0	3.41	7.93	0.72	4.5	3.78	7.55
1 September	0.82	4.1	3.45	6.42	0.65	4.9	3.48	7.78	0.71	4.6	3.70	7.70
Budburst	**0.86**	**3.2**	**2.54**	**5.00**	**0.65**	**4.4**	**3.39**	**7.73**	**0.78**	**4.3**	**3.27**	**7.13**

The lines in bold correspond to the t_0 date selected.
$>Q_{75}$ are the values of the average difference between predicted and observed flowering dates above the upper quartile.

following equations:

$$R^2 = \frac{(\text{SStot} - \text{SSres})}{\text{SStot}} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\text{SSres}}{n}} \quad (3)$$

$$\text{MAD} = \frac{\sum_{i=1}^{n} |\text{Xobs}_i - \text{Xpre}_i|}{n} \quad (4)$$

where SStot is the Total Sum of Squares, SSres is the Residual Sum of Squares, n the number of observations and Xobs_i and Xpre_i are, respectively, the observed values and predicted values.

The average difference between predicted and observed flowering date above the upper quartile ($>Q_{75}$) was also used in the selection of the best model in the estimation process.

For the best-fitted model, a linear regression through the origin between predicted and observed flowering dates was performed. The hypothesis is that the concordance line of this regression passes through the origin and has a coefficient of regression (b_0) of unity, indicating the absence of bias and showing no significant differences between predicted and observed flowering date. An analysis of frequencies of the differences between predicted and observed flowering dates was also performed for each test site.

Results

Regional phenological time series

The analysis of long-term grapevine phenological observations in three regions of Portugal (Table 2) showed that there is a marked inter-annual variation of both budburst and flowering phenological dates among grape varieties.

The budburst dates vary from Day of the Year (DOY) 74 (15 March for Castelão) to DOY 95 (5 April for Pedernã) and flowering occurs between DOY 141 (21 May for Castelão e Touriga Nacional) and DOY 154 (3 June for Vinhão and Pedernã) and the period between budburst and flowering has an average duration of 59 (Pedernã, Trajadura and Espadeiro Tinto) to 69 days (Fernão Pires) (Table 2).

The average budburst date in Vinhos Verdes was DOY 88 (29 March) and in Lisbon was DOY 78 (19 March). In the Vinhos Verdes region, the AVV average budburst date was earlier than for FEL (DOY 86, 27 March, and DOY 99, 9 April, respectively). The same tendency was observed for the average flowering date, which was later in Vinhos Verdes (DOY 151–31 May) compared with Lisbon (DOY 143–23 May). In Vinhos Verdes, the AVV average flowering date was earlier than the FEL (DOY 150, 30 May, and DOY 155, 4 June, respectively).

Descriptive statistical analysis and an inter-varieties comparison for budburst and flowering dates were performed (Table 2). The varieties studied were compared for the occurrence of budburst and flowering date and based on Lopes *et al.* (2008) and Robinson *et al.* (2012) were classified as early varieties (Avesso, Chasselas, Fernão Pires, Castelão and Touriga Nacional) and late varieties (Pedernã, Trajadura, Espadeiro Tinto and Vinhão) (Table 2).

Modelling grapevine phenology

Model estimation

In the iterative process, estimation of the models was tested for three forced t_0 dates: budburst date, 1 January and 1 September. The differences between the tested t_0 dates were very small in terms of efficiency within and between each type of model (Table 3), with none of the models performing significantly better. Nonetheless, in each model, the budburst date resulted in the highest R^2 and lowest RMSE and MAD. It was also observed that the

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Table 4. Summary of the results from the estimation process second phase where t_0 date was budburst and for each model, an intermediate set of values of the estimated parameters were optimized

	Fernão Pires AVV				Fernão Pires TOV				Loureiro AVV			
Iteration step	Parameters	R^2	RMSE	$>Q_{75}$	Parameters	R^2	RMSE	$>Q_{75}$	Parameters	R^2	RMSE	$>Q_{75}$
Growing Degree Days (GDD) – T_b												
Fitted	7.89	0.87	3.1	4.97	9.13	0.71	4.0	6.58	8.37	0.80	4.1	6.72
1	7	0.86	3.2	5,10	7	0.69	4.2	6.83	7	0.78	4.3	7.47
2	**8**	**0.86**	**3.1**	**4.92**	**8**	**0.70**	**4.1**	**6.73**	**8**	**0.80**	**4.1**	**6.92**
3	9	0.83	3.5	5.42	9	0.71	4.2	6.62	9	0.78	4.3	7.10
4	10	0.83	3.5	6.90	10	0.7	4.1	6.48	10	0.74	4.7	8.35
Growing Degree Days (GDD) Triangular – T_{min}, T_{opt}, T_{max}												
Fitted	7.90; 23.01; 30.70	0.87	3.1	4.97	8.96; 22.89; 29.77	0.72	3.9	6.22	8.37; 22.39; 29.06	0.80	4.1	6.75
1	8; 23; 29	0.78	3.9	4.98	8; 23; 29	0.72	4.0	6.48	8; 23; 29	0.80	4.1	6.88
2	8; 23; 30	0.87	3.1	4.95	8; 23; 30	0.72	4.0	6.50	8; 23; 30	0.80	4.1	6.88
3	**8; 23; 31**	**0.87**	**3.1**	**4.97**	**8; 23; 31**	**0.72**	**4.0**	**6.47**	**8; 23; 31**	**0.80**	**4.1**	**6.87**
4	9; 23; 29	0.83	3.4	5.43	9; 23; 29	0.72	3.9	6.27	9; 23; 29	0.79	4.2	7.07
5	9; 23; 30	0.83	3.5	5.43	9; 23; 30	0.72	3.9	6.33	9; 23; 30	0.79	4.2	7.07
6	9; 23; 31	0.83	3.5	5.43	9; 23; 31	0.72	3.9	6.33	9; 23; 31	0.79	4.2	7.05
UniFORC – d: fitted, *e*												
Fitted	16.22	0.86	3.2	5.00	14.77	0.65	4.4	6.90	16.34	0.78	4.3	6.98
1	14	0.85	3.3	5.48	14	0.66	4.3	7.23	14	0.78	4.3	7.10
2	15	0.86	3.1	5.08	15	0.70	4.1	6.53	15	0.79	4.3	6.92
3	**16**	**0.87**	**3.0**	**4.88**	**16**	**0.72**	**4.0**	**6.22**	**16**	**0.79**	**4.2**	**6.97**

The lines in bold correspond to the parameters and respective models selected. The $>Q_{75}$ column are the values of average difference between predicted and observed dates above the upper quartile.
$>Q_{75}$ are the values of average difference between predicted and observed flowering dates above the upper quartile.

Table 5. Goodness-of-fit indicators of the model estimation and validation process using the dataset for 15 grapevine varieties in three regions (AVV, TOV and FEL)

Grape varieties	GDD $T_b = 8$			GDD Triangular $T_{min} = 8.0$, $T_{opt} = 23$, $T_{max} = 31$			UniFORC D = fitted; $e = 16.0$				
	RMSE	R^2	MAD	RMSE	R^2	MAD	RMSE	R^2	MAD	R^2[1:1]	b_0[1:1]
Arcos de Valdevez (AVV)											
Alvarinho	3.4	0.83	2.90	3.4	0.83	2.93	3.3	0.84	2.73	0.84	1.01
Avesso	3.7	0.70	2.99	3.7	0.70	3.01	3.3	0.76	2.44	0.77	0.99
Azal	3.7	0.78	2.95	3.7	0.78	2.86	3.3	0.82	2.68	0.82	1.00
Chasselas	3.4	0.77	3.23	3.4	0.78	3.20	3.1	0.81	2.35	0.82	0.99
Fernão Pires[a]	3.1	0.86	2.53	3.1	0.87	2.49	3.0	0.87	2.48	0.86	1.00
Loureiro[a]	4.1	0.80	3.20	4.1	0.80	3.20	4.2	0.79	3.34	0.79	1.00
Pedernã	4.0	0.84	3.04	4.0	0.84	2.99	3.4	0.89	2.95	0.88	1.00
Trajadura	4.5	0.84	3.28	4.5	0.84	3.33	4.2	0.86	3.20	0.86	1.00
Castelão	4.1	0.59	3.49	4.1	0.59	3.48	3.3	0.73	2.38	0.73	1.00
Espadeiro tinto	3.4	0.83	2.73	3.4	0.83	2.68	3.3	0.83	2.63	0.83	1.00
Padeiro Basto	4.1	0.78	3.13	4.0	0.78	3.11	4.2	0.77	3.16	0.77	0.99
Vinhão	4.2	0.74	3.62	4.2	0.74	3.51	4.8	0.74	3.34	0.75	1.00
Mean	3.8	0.78	3.09	3.8	0.78	3.07	3.6	0.81	2.81	0.81	1.00
Torres Vedras (TOV)											
Alvarinho	3.6	0.78	3.12	3.7	0.78	3.13	3.7	0.78	2.85	0.78	1.00
Chasselas	3.8	0.74	3.25	3.9	0.74	3.23	3.8	0.74	3.25	0.72	1.00
Fernão Pires[a]	4.1	0.70	3.36	4.0	0.72	3.23	4.0	0.71	3.36	0.70	1.00
Loureiro	3.9	0.79	3.25	3.9	0.79	3.31	3.9	0.79	3.27	0.78	1.00
Aragonez	3.8	0.79	3.18	3.8	0.79	3.18	3.6	0.81	3.11	0.79	1.00
Baga	4.0	0.70	3.22	3.8	0.72	3.03	3.9	0.72	3.15	0.71	1.00
Castelão	3.8	0.76	2.99	3.9	0.75	3.05	3.8	0.76	3.08	0.75	1.00
Padeiro Basto	3.7	0.78	2.98	3.8	0.77	3.04	3.1	0.85	2.36	0.79	1.00
Touriga Nacional	3.2	0.82	2.62	3.3	0.81	2.63	3.2	0.83	2.54	0.82	1.00
Mean	3.8	0.76	3.11	3.8	0.76	3.09	3.7	0.78	3.00	0.76	1.00
Felgueiras (FEL)											
Loureiro	6.3	0.67	4.95	6.4	0.67	5.14	6.4	0.66	5.01	0.66	1.00
Pedernã	6.6	0.67	5.64	6.7	0.65	5.95	6.3	0.69	4.73	0.67	1.01
Trajadura	5.8	0.64	4.37	5.8	0.64	4.59	5.8	0.64	4.13	0.62	1.00
Espadeiro tinto	6.3	0.73	5.70	6.6	0.71	5.90	6.4	0.73	5.38	0.71	1.00
Mean	6.3	0.68	5.17	6.4	0.67	5.39	6.4	0.67	4.99	0.67	1.00
Means											
Overall	4.6	0.74	3.79	4.7	0.74	3.85	4.6	0.75	3.60	0.75	1.00
Estimation	3.8	0.79	3.03	3.7	0.80	2.97	3.7	0.79	3.06	0.78	1.00
Validation	4.3	0.75	3.56	4.4	0.75	3.59	4.2	0.77	3.29	0.76	1.00
Validation White	4.3	0.76	3.47	4.3	0.76	3.51	4.1	0.78	3.25	0.77	1.00
Validation Red	4.1	0.75	3.37	4.1	0.75	3.36	4.0	0.78	3.11	0.77	1.00

[a]Variety used in the model's estimation.
R^2[1:1] and b_0[1:1] are, respectively, the coefficient of determination and the coefficient of regression through the origin between predicted and observed values for the UniFORC model.

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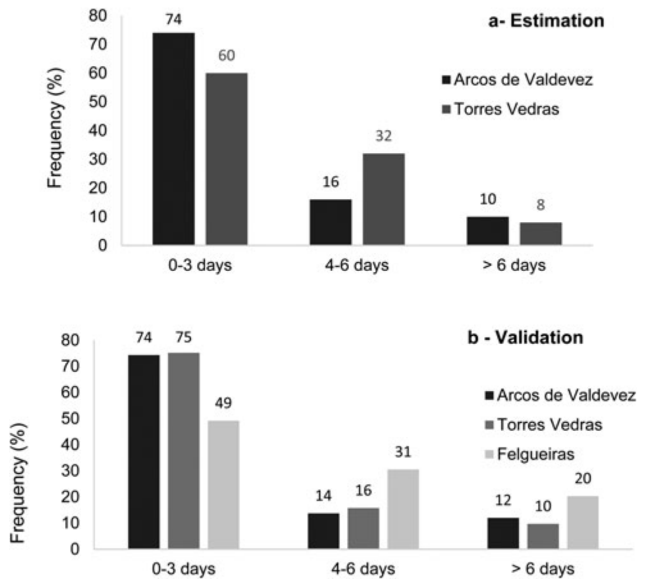

Fig. 5. Frequency in the percentage of difference in days between predicted and observed flowering date for Loureiro, AVV, and Fernão Pires, AVV and TOV (*a*), used in the UniFORC model estimation (5a) and for UniFORC validation (5b) with 13 grapevine varieties in three regions (AVV, TOV and FEL).

average difference between predicted and observed dates above the upper quartile were smaller (differences of 1 and 2 days).

Furthermore, the models considering t_0 as the budburst date presented a similar intermediate range of values for the estimated parameter, which was not observed for the others. These results allowed selection of budburst as the best overall t_0 date to be used in the next steps of the optimization process.

Using the observations corresponding to Fernão Pires in the AVV region, Fernão Pires in the TOV region and Loureiro in the AVV region and the budburst date as t_0, it was observed that the estimated parameters converge to the following values, respectively (Table 4, values fitted): (i) GDD model the values of T_b were 7.89, 9.13 and 8.37 °C; (ii) GDD Triangular model the values of $T_{\min}$ were 7.90, 8.96 and 8.37 °C, the values of T_{opt} were 23.01, 22.89 and 22.39 °C and for the $T_{\max}$ were 30.70, 29.77 and 29.06 °C; (iii) UniFORC model the values of *e* were 16.22, 14.77 and 16.34 °C. Based on these results, in a second iteration process the model's parameters were constrained to a fixed range of values: (i) GDD model T_b assumed values between 7 and 10 °C; (ii) GDD Triangular model $T_{\min}$ assumed values ranging between 8 and 9 °C, $T_{\max}$ between 29 and 31 °C and T_{opt} the value of 23 °C since the temperatures in the fitted model converged consistently to this value; (iii) UniFORC model the parameter *e* assumed values between 14 and 16 °C. In this second iteration step, as observed in the decision process to select the t_0 date, the efficiency of the estimated models was quite similar. Therefore, the choice of the best parameter set for each model was based on the lowest average difference between predicted and observed dates above the upper quartile (Table 4).

In the GDD model the T_b was fixed at 8 °C and in the GDD Triangular model $T_{\min}$ at 8 °C, T_{opt} at 23 °C, $T_{\max}$ at 31 °C and the F^* was fitted. In the UniFORC model the value of *e* was fixed at 16 °C and the *d* and F^* were fitted (Table 4).

Model validation

The results of the estimation and external validation with the independent dataset of the flowering dates from 15 grapevine varieties are presented in Table 5. The overall mean R^2, RMSE and MAD values obtained in the estimation and in the validation steps for each tested model were similar: (i) GDD model R^2: 0.79 *v.* 0.75, RMSE: 4 days and MAD: 3 *v.* 4 days; (ii) GDD Triangular model R^2: 0.80 *v.* 0.75, RMSE: 4 days and MAD: 3 *v.* 4 days; (iii) UniFORC model R^2: 0.79 *v.* 0.77, RMSE 4 days and MAD: 3 days (Table 5). The same pattern was observed for white *v.* red varieties and for earlier *v.* later varieties.

In fact, the only variety with large differences was Castelão in AVV for the GDD and GDD Triangular models with a R^2 value of 0.59 and RMSE of 4.11, while for the UniFORC model the statistical indicators were similar to those found for the other varieties. This can be explained by the small number of observations for this variety when compared with the others (only 8 years).

Model selection

Along the estimation and validation steps, the three phenological models tested presented minimal differences in terms of efficiency in forecasting flowering dates, with equal or very similar R^2 values and MAD differences less than a fraction of 1 day between the models. However, the UniFORC model ($e = 16$ °C), when compared with the two GDD versions tested, presented overall a slightly higher R^2 (0.75), particularly in the validation step in AVV region for the varieties Castelão (0.59 *v.* 0.73), Avesso (0.70 *v.* 0.76), Azal (0.78 *v.* 0.82) and Pedernã (0.84 *v.* 0.89) and in TOV region for Padeiro Basto (0.78 *v.* 0.85). Also, it was the model with the lowest overall RMSE (4.55) and MAD (3.60) (Table 5) and the best performance in the validation process with a mean R^2 of 0.77, RMSE of 4.19 days and MAD of 3.29 days. This model showed the best results for the white and red varieties tested in terms of R^2 (0.78), RMSE (4.11 *v.* 3.95) and MAD (3.25 *v.* 3.11).

Figure 5 presents the differences in a number of days between predicted and observed flowering dates attained by the UniFORC model plotted against the frequency of occurrence. Of the 75 observations used in the model estimation (Loureiro, AVV and Fernão Pires, AVV and TOV), about three-quarters of the cases had differences between predicted and observed flowering date <3 days (Fig. 5a). In the model validation, using 398 observations from 13 grapevine varieties in three regions (AVV, TOV and FEL), the differences between predicted and observed values were <3 days in 0.74 of the cases in AVV and TOV and 0.49 for FEL (Fig. 5b).

The results of the linear regression through the origin between predicted and observed flowering dates for the UniFORC model are presented in Table 5. Figure 6 highlights the results for the variety Loureiro in AVV (which was used in the estimation process) and TOV regions and for the variety Espadeiro tinto in AVV and FEL. Overall, the regression coefficients (b_0) are close to 1.0 for both estimation (average $b_0 = 1.0$) and validation (average $b_0 = 1.0$) indicating, therefore, the absence of bias.

Discussion

Three temperature-based phenological models were estimated and validated to predict the timing of flowering using a long phenological dataset for a large number of grapevine varieties grown in two Portuguese wine regions (Vinhos Verdes and Lisbon).

The parameterization of the models was achieved by an iterative process. In the first estimation phase, the varieties with the longest time series of phenological data for AVV (Fernão Pires and Loureiro) and TOV (Fernão Pires) were used in order to

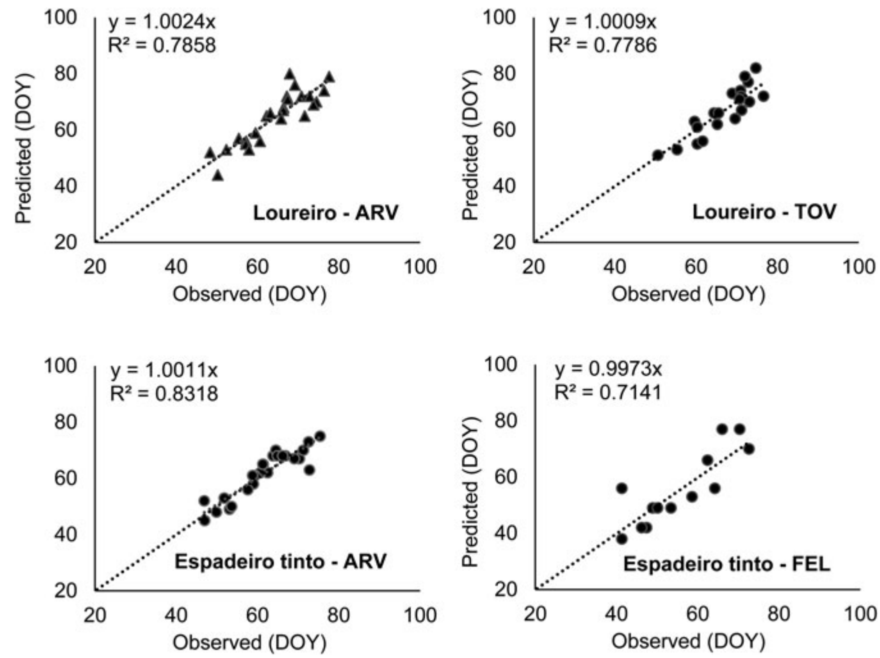

Fig. 6. Predicted and observed dates of flowering for two varieties using the UniFORC model. Closed triangles (▲) represent data used for the model estimation and closed circles (•) represent data used for the model validation.

determine for each model type – GDD, GDD Triangular and UniFORC – the fixed parameter estimates that best predict a flowering date. As such, the temperatures chosen to incorporate into these models were those that best fit the different data series. Therefore, the base temperature (T_b) for the GDD model was established at 8 °C. In the GDD Triangular model the minimum (T_{min}), optimal (T_{opt}) and maximum (T_{max}) temperatures were fixed at 8, 23 and 31 °C, respectively. Several base temperatures have been mentioned in the literature as the optimum threshold above which temperature summation is efficient for growth. In *Vitis vinifera* L., 10 °C has been suggested by several authors for the base/minimum temperature (Winkler *et al.*, 1974; Huglin and Schneider, 1986; Carbonneau *et al.*, 1992; Riou, 1994). Parker *et al.* (2011), proposed a general temperature-based phenological model for vineyard flowering using data from France, Italy, Switzerland and Greece where a base temperature of 0 °C was found to give the best fit. For instance, in Portugal Fraga *et al.* (2016) proposed a base temperature of 9.2 °C for Fernão Pires and 8.9 °C for Castelão. The grapevine phenotypic plasticity can explain this range of base temperatures, with the value being influenced not only by intrinsic factors of the plant but also by the local environment (Chuine *et al.*, 1999). In the current study, it was observed that the efficiency gain when a range of T_b between 7 and 10 °C was tested, was small.

The interval between 25 and 35 °C was considered the optimal range of temperature for photosynthesis and temperatures above 35 °C appear to have a negative effect on photosynthetic processes (Greer and Weedon, 2012). In fact, the T_{opt} assumed in the current study (23 °C) is close to the optimum temperature (25 °C) proposed by Caffarra and Eccel (2010) for grapevine phenological development.

In the current study, the date for the beginning of accumulation of heat units (t_0) was fixed as the budburst date. During the study period, this phenological stage occurred on average during March (29 March in Vinhos Verdes and 19 March in Lisbon), which is not far from the value of 60 days proposed by Parker *et al.* (2011) as the initial date for the thermal summation. The period between budburst and flowering is shorter (from 59 to 67 days) compared with the other periods tested (1 September – Flowering and 1 January – Flowering), which implies the existence of less meteorological and biological variability that influence the timing of flowering. This would consequently increase the accuracy of the phenological model. On the other hand, the inter-annual variability of budburst date reflects the prevailing conditions of chilling accumulation during the dormancy phase and indirectly incorporates this period into the model. Indeed it would be interesting to ascertain if the optimization of a two-phase model considering the successive stages of dormancy and growth, using an Alternating, Parallel or Sequential approach, could increase the accuracy of the models. Nonetheless, the models developed considering budburst as the start date for thermal accumulation provide tools for wine producers to incorporate the local-specific variability of budburst dates to predict the date of flowering.

In a second phase of the process, validation was performed by testing the three estimated models with fixed parameters on 13 varieties grown in the Vinhos Verdes (AVV and FEL) and Lisbon (TOV) wine regions. Therefore, the models (GDD, GDD Triangular and UniFORC) were compared using 473 observations of flowering date. Overall, the accuracy in forecasting flowering dates was very similar between the three models tested for all varieties, with high R^2 and low RMSE and MAD <4 days in AVV and TOV and <6 days in FEL. This similarity between the models indicates that the parameter estimates allow a similar prediction of flowering date, varying only in the type of response function of the plant to temperature. Nevertheless, the UniFORC model presented the best results overall, with R^2 higher than 0.75 in 0.67 and 0.65 of cases, respectively, for the estimation and validation data sets, which indicates that most of the observed annual flowering dates were explained by this model. In addition, from the biological point of view the phenological development of most plant species is continuous and non-linear (Chuine *et al.*, 2003) and the UniFORC model represents this type of physiological response of the plant to ambient temperature, even though two parameters (F^* and d) must be fitted.

With the UniFORC model, MAD was on average 2.81 days in AVV and 3.00 days in TOV. In FEL, the average MAD was 4.99 days. In the current study, the number of days between phenological observations in the field was 3/4 days in the case of AVV and TOV and 6/7 days in FEL. Therefore, the errors obtained are lower than the frequency of field observations.

Shorter intervals between field phenological observations can improve the quality of data and consequently the precision of models to predict a flowering date. Daily field observations can be made using new technologies such as the use of satellite remote sensing and digital imaging systems (e.g. using multiple flashes camera for image acquisition; Mager *et al*., 2014).

In the current study, the number of phenological observations is unbalanced between sites and across varieties, and between estimation and validation data sets. In fact, the longest time-series (25 years) were used in the estimation process that allows great inter-annual variability to be taken into account. In the validation phase more variable time series, with 8–25 years, were used. However, the statistical indicators of the series with different observations were very similar, which corroborates the robustness of the results.

Conclusion

The current paper shows how grapevine flowering date can be estimated using temperature-based phenological models across different genotypes (grape varieties) and environments (wine regions) in Portugal. Three models were tested: Spring Warming (GDD model), Spring Warming modified using a triangular function – GDD triangular and UniFORC model, which considers an exponential response curve to temperature. The accuracy for predicting grapevine flowering date was very similar between them but, a UniFORC model with fixed optimized parameters starting from the budburst date presented the best overall fit.

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Conflicts of interest. None.

Ethical standards. Not applicable.

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