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Development of a predictive model of phenology in grapevines cv. Cabernet Sauvignon under conditions of high spatial variability in Maule Valley

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Abstract

Phenology monitoring is indispensable for planning vine managements. This study aimed to develop a prediction model of phenology. This was applied to Cabernet Sauvignon variety, grown under high and low spatial variability field located in the Maule Valley (Chile). The predictive model was based on Mitscherlich monomolecular equation, where the dependent variable corresponded to the phenological stages and the independent variable corresponded to the degree-days (base 10°C). Model calibration was performed with data from 2 seasons (2009-10 and 2010-11), while model validation was performed using data from 2011-2012 season for the field under study, as well as a separate dataset coming from three Cabernet Sauvignon fields grown under low spatial variability, for which phenological information from 2000-2001 season was available. The results showed that the proposed model had a high degree of fit between estimated and observed phenological stages ($R^2 > 0.98$ and standard deviation between 1.0 and 1.84 phenological units), suggesting that the model proposed can be used to predict phenology stages in Cabernet Sauvignon vineyards established under high and low spatial variability and different management systems in the Maule Valley.

Keywords: grapevine, growing degree-days, phenological stages, precision agriculture, *Vitis vinifera*

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Desarrollo de un modelo predictivo de fenología en vides cv. Cabernet Sauvignon bajo condiciones de alta variabilidad espacial en el Valle del Maule

Resumen

El monitoreo de la fenología es indispensable para planificar el manejo de los viñedos. Este estudio tuvo como objetivo desarrollar un modelo de predicción de la fenología. Este modelo se aplicó a la variedad Cabernet Sauvignon, cultivada en un campo con alta y baja variabilidad espacial ubicado en el Valle del Maule (Chile). El modelo predictivo se basó en la ecuación monomolecular de Mitscherlich, donde la variable dependiente correspondió a los estados fenológicos y la variable independiente correspondió a los grados día (base 10 °C). La calibración del modelo se realizó con datos de 2 temporadas (2009-2010 y 2010-2011), mientras que la validación del modelo se llevó a cabo utilizando datos de la temporada 2011-2012 para el campo en estudio, así como un conjunto de datos independiente proveniente de tres campos de Cabernet Sauvignon cultivados con baja variabilidad espacial, para los cuales se disponía de información fenológica de la temporada 2000-2001. Los resultados mostraron que el modelo propuesto presentó un alto grado de ajuste entre los estados fenológicos estimados y observados ($R^2 > 0.98$ y desviación estándar entre 1.0 y 1.84 unidades fenológicas), lo que sugiere que el modelo propuesto puede ser utilizado para predecir los estados fenológicos en viñedos de Cabernet Sauvignon establecidos bajo alta y baja variabilidad espacial y diferentes sistemas de manejo en el Valle del Maule.

Palabras clave: uvas, grados-día acumulados, estados fenológicos, agricultura de precisión, *Vitis vinifera*

Desenvolvimento de um modelo de previsão da fenologia em videiras cv. Cabernet Sauvignon em condições de alta variabilidade espacial no Vale do Maule

Resumo

A monitorização da fenologia é essencial para planear a gestão da vinha. O objetivo deste estudo foi desenvolver um modelo de previsão fenológica para videiras Cabernet Sauvignon em um vinhedo com alta variabilidade espacial localizado no Vale do Maule durante as temporadas 2009-2010, 2010-2011 e 2011-2012. O modelo de previsão foi desenvolvido com base na equação monomolecular de Mitscherlich, onde a variável dependente correspondeu aos estádios fenológicos e a variável independente aos graus-dia (base 10°C) que foram registados desde o abrolhamento até à colheita da videira. A validação do modelo foi realizada utilizando dados da época 2011-2012 do ensaio, bem como um conjunto de dados obtidos de três vinhedos localizados perto de Talca, para os quais havia informação fenológica disponível da temporada 2000-2001. Os resultados mostraram que o modelo proposto teve um alto grau de ajuste entre os estágios fenológicos estimados e observados ($R^2 > 0.98$ e desvio padrão entre 1.0 e 1.84 unidades fenológicas), sugerindo que o modelo proposto poderia ser usado para prever estágios fenológicos em vinhedos de Cabernet Sauvignon estabelecidos sob alta e baixa variabilidade espacial e sob diferentes sistemas de manejo no Vale do Maule.

Palavras-chave: uvas, graus-dias acumulados, unidades fenológicas, agricultura de precisão, *Vitis vinifera*

1. Introduction

The study of vine growth stages, such as budburst, flowering and veraison, is called vine phenology, which are events that are repeated every season and which development is mainly related to climatic factors[1][2]. The knowledge and monitoring of the phenological stages of the grapevine during the season allow the planning of production, such as irrigation, fertilization, phytosanitary management and harvest[1]. Based on this, some authors have proposed methodologies based on vine monitoring to powdery mildew management, which allowed to perform specific applications at the phenological stages where the plant is most susceptible, reducing the number of applications of phytosanitary products[3]. Regarding irrigation management, it is commonly known that the application of regulated deficit irrigation in specific vine phenological stages improves grape quality[4][5].

Phenology monitoring as a management tool has provided several investigations at different spatial sampling scales. Thus, models have been developed to predict phenological events, with the aim of planning viticultural work at the level of the viticultural plots[2][3][4][5]. Likewise, other authors have used phenology models to determine the impact of climate change on the phenological development of grapevine at large spatial scales[6][7][8]. In addition, studies about spatial variability of grapevine phenology at the regional level have been carried out to determine optimal soil and climatic zones for the production of quality grapes and to establish temporal trends in berry maturity in large geographic areas[9][10][11].

Most of the research conducted on grapevine phenology has focused mainly on large-scale production studies, despite the fact that, from a practical point of view for the viticulturist, the basic management unit for the planning of agricultural work is the vineyard block[12]. Traditionally, viticulturists make few phenological observations at the vineyard block level, which are extrapolated to the entire production unit, without considering the natural spatial variability of plots, which often means losses of inputs and energy, making the viticultural system less sustainable. Currently, it is known that the vineyard block is not a homogeneous management unit with respect to its phenological cycle, and it is postulated that in agriculture, especially in viticulture, there is a high spatial variability in vineyard blocks, understood as existing differences in a basic productive unit, which can be associated mainly with differences in the soil or in the management of the block[2][4][11][12]. In addition, it has been reported that edaphoclimatic conditions such as soil texture, soil and air temperature, altitude and water holding capacity would have an important effect on the phenological development of grapevines[13][14][15].

In the last decades, the use of precision agriculture (PA) tools has made it possible to quantify the spatial variability existing in vineyard blocks[2][5], and to study its effects on productive parameters such as vegetative growth, yield, berry maturity and berry quality components[9][10][13]. In addition, it has also been possible to quantify and manage this variability, proposing homogeneous management zones within a vineyard block[12][15][16][17].

Cabernet Sauvignon is one of the most important grapevine varieties cultivated worldwide, even in Chile[18]. It is originally from Bordeaux (France), but currently it is planted in vineyards from different regions. Cabernet Sauvignon has been important in the countries of the “New World”, providing awarded wines in various competitions worldwide[18]. It has allowed these countries to position themselves in the world wine market[18]. However, the rise of temperatures and the decrease of precipitations due to climate change trigger advanced maturation, affecting grape and wine quality, including the viticultural suitability of this variety in Chile[19][20].

Thereby, the aim of this research was to develop and evaluate a predictive model of phenology in Cabernet Sauvignon grapevines grown under conditions of high spatial variability in the Maule Valley (Chile).

2. Materials and Methods

2.1 Experimental Trial

The study was conducted in a 1.56 ha commercial Cabernet Sauvignon vineyard located at the Panguilemo Experimental Station of the University of Talca (Maule Valley, Chile; 35°22.2' S, 71°35.39' W, 121 m.a.s.l.) during the 2009-10, 2010-11 and 2011-12 growing seasons. The ungrafted vineyard was established in 1998 with a row spacing of 1.5 m above the row and 3.0 m between rows with an E-W orientation. The vineyard was trained on a 2.0 m vertical shoot position trellis system, pruned in a bilateral cordon and irrigated with a gravity system. The region is characterized by a Mediterranean climate. The soil texture is clay loam with a rooting depth of 150 cm, and the soil is classified as part of the Talca series (Thermic Ultic Haploxeralf)[21]. The vineyard was managed according to the conventional agricultural practices used in the commercial vineyards of

central Chile in terms of canopy management, fertilization, pest, and disease control, pruning and irrigation, over all the seasons of the study period.

An automatic weather station (Adcon Telemetric, A730, Klosterneuburg, Austria) installed under reference conditions was used to measure air temperature, relative humidity, solar radiation, precipitation, wind speed and direction, as exposed by Verdugo-Vásquez and others[4]. This information was used to estimate the reference evapotranspiration (ET_0), using the Penman-Monteith equation[22] and the growing degree days (GDD) accumulation until harvest. Sum of GDD was calculated as the sum of the daily difference between the average air temperature minus 10 ºC[23].

2.2 Model Development

Phenology measurements were made spatially using a regular grid of 18 sites within the vineyard (**Figure 1**), which were geo-referenced using a Differential Global Positioning System (DGPS) (Pathfinder Pro XRS). Phenology determinations were performed from budburst to veraison every 7 days, as was previously published by Verdugo-Vásquez and others[4].

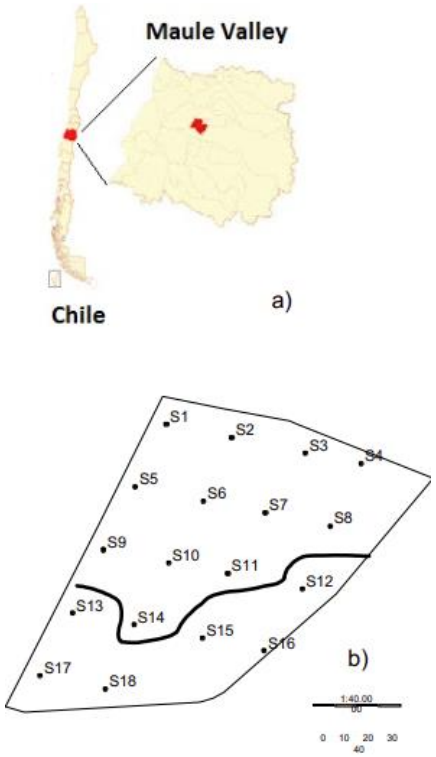

Figure 1. Location of the Maule Valley in Chile (a) and experimental plot showing the distribution of the 18 phenology sampling sites. Where Si represents sampling site number i. (b). Black line divides the vineyard into the two identified zones.

For each sampling site, one vine was sampled, and the first 30 shoots were measured, obtaining average values per sampling site. In these shoots, the vine phenological development was evaluated using the phenological scale of Eichhorn and Lorenz modified by Coombe[24], which considers measurements of leaf number, shoot length (cm), berry diameter (mm) and soluble solids (ºBrix). Berry soluble solid content was measured using a self-compensated refractometer (model BRIX30, Leica, USA), selecting eight bunches randomly from each plant, from which two berries were sampled from the upper, middle and lower part of the bunch, respectively, obtaining a total of 48 berries sampled per plant. The phenological scale assigns a number to each measurement, which allows to obtain a quantitative variable to be added in the mathematical models.

Phenological stages were registered between budburst (Stage 4) to technological harvest (Stage 38), every 7 days during the three study seasons. Due to the high spatial variability of grapevine phenology within the vineyard, it was previously divided into 2 management zones, which showed significant differences in their phenological evolution[9]. The zone 1 of the viticultural plot has the most advanced phenological stages during all seasons and represents 78% of the area of the plot, while zone 2 has more delayed phenological stages and corresponds to the remaining 22% of the area. The data from the 2009-10 and 2010-11 seasons, from both zones of the viticultural plots, were used to construct the predictive phenology model. This model was based on the methodology proposed by Ortega-Farias and others[5], who used the monomolecular Mitscherlich equation (**Eq. 1**), which establishes that growth is constant, with no inflection point.

$$W = W_f - (W_f - W_0)e^{-kt} \quad \text{(Eq. 1)}$$

Equation 1. Monomolecular Mitscherlich equation. W corresponds to the vine phenological stage based on the Eichhorn and Lorenz scale modified by Coombe[24]; W_0 is the phenological stage of budburst (Stage 4), W_f is the phenological stage of technological harvest (Stage 38); k represents the phenological development rate and t is the growing degree days (GDD) (ºC d^{-1}).

The GDD was calculated from budburst to technical harvest, using the equation proposed by Bindi and others[26] (**Eq. 2**). The base temperature used corresponds to 10 °C[23]. The parameter k of equation (**Eq. 1**) was determined using the "Curve Fitting Toolbox" tool of the Matlab© software.

$$GDD = \sum_{i=1}^{n} (T_{Xi} - T_u) \quad \text{(Eq. 2)}$$

Equation 2. Growing degree days (GDD) equation. GDD corresponds to the cumulative degree days (°C d^{-1}); T_{Xi} is the average daily temperature (°C); T_u is the threshold temperature (10 °C); i=1 corresponds to the day of budburst, and n to the day of technological harvest.

2.3 Model Evaluation

The validation of the proposed model was carried out using data from the 2011-2012 season. In addition, a database external to the trial was used, corresponding to three vineyards (cv Cabernet Sauvignon) located near Talca, in which phenological and climatic information was available from the 2000-2001 season. In this case, the phenology registrations were carried out by the winegrowers, using the same phenological scale used in this study. In each vineyard, five plants of a row were selected and marked in order to follow the phenology stages from budburst to technological harvest[25]. Soluble solids measurements were carried out in four replicates per vineyard, obtaining 40 berries per replicate. Thus, the data measured represent a general average in each vineyard plot.

The first (P1: 1.7 ha) selected vineyard to model validation was planted in 1990 with a row spacing of 0.9 m above the row and 2.9 m between rows with a N-S orientation, trained in Scott-Henry trellis system and irrigated with a furrow system. The second (P2: 4.0 ha) was planted in 1955 with a row spacing of 2.0 m above the row and 4.0 m between rows with an E-W orientation, trained in overhead trellis system and irrigated with a gravity system. The third (P3: 6.0 ha) was planted in 1995 with a row spacing of 1.0 m above the row and 3.0 m between rows with a N-S orientation, trained in vertical shoot position system and irrigated with a gravity system.

2.4 Statistical Analysis

To determine fitness of the proposed model, the following statistical indicators between the observed phenological stages (y_{obs}) and the phenological stages estimated (y_{est}) by the model were estimated[27].

$$SD = \sqrt{\frac{\sum(Y_{obs} - Y_{est})^2}{n-1}} \quad \text{(Eq. 3)}$$

Equation 3. Standard deviation (SD) equation. Y_{obs} corresponds to observed phenological stages; Y_{est} to estimated phenological stages, and n corresponds to number of observations.

$$MAE = \frac{\sum|Y_{obs} - Y_{est}|}{n} \quad \text{(Eq. 4)}$$

Equation 4. Mean absolute error (MAE) equation. Y_{obs} corresponds to observed phenological stages; Y_{est} to estimated phenological stages, and n corresponds to number of observations.

$$EF = 1 - \frac{\sum(Y_{obs} - Y_{est})^2}{\sum(Y_{obs} - Y_{mean\ est})^2} \quad \text{(Eq. 5)}$$

Equation 5. Modelling efficiency (EF) equation. Y_{obs} corresponds to observed phenological stages; Y_{est} to estimated phenological stages, and $Y_{meanest}$ corresponds to the mean of the estimated phenological stages.

A linear regression analysis was also performed between the observed values (X axis) and the estimated phenology values (Y axis)[27]. In addition, an analysis of variance for statistical significance was also performed. The statistical analyses and tests were considered significant for a probability value of $p \leq 0.05$, using the Statgraphics 5.1 program (Statpoint Inc., Virginia, USA).

3. Results and Discussion

3.1 Climatic Characterization

The climatic characterization of the 2009-10, 2010-11 and 2011-12 seasons is presented in

Table 1. It can be observed that the first two studied seasons were similar to each other and slightly different from the 2011-12 season. Maximum (Max T) and minimum (Min T) air temperature as well as reference evapotranspiration (ET_0) were higher during the third season, from budburst to technological harvest (2011-12), but precipitation was lower, especially during the period between budburst and flowering. Consequently, the climatic water deficit (P-ET0) was about 12% higher during the third season compared to the first two seasons.

Table 1 shows that there was an increase in Min T and Max T from budburst until the veraison, with a subsequent decrease between veraison and harvest. The GDD were similar in the budburst and flowering periods with ranging values between 253- and 273-degree days. A greater difference between seasons for the other phenological periods, such as the period between flowering and fruit set, was observed. Thermal accumulation during the growing season (budburst to harvest) ranged from 1324 to 1450 GDD, which are considered adequate for a correct ripening of Cabernet Sauvignon grapes[28]. The 2011-12 season presented the highest

thermal accumulation, being the period between fruit set and veraison the one with the highest thermal sum. This represented 574 GDA, equivalent to 40% of the total thermal sum.

3.2 Model Development

The model of phenology performed with data from a vineyard with high spatial variability is presented in **Table 3** The value of the estimated parameter k was 0.0028 (confidence interval from 0.002793 to 0.002934, **Table 3**), which corresponds to the rate of phenology development, as a function of GDD. Ortega-Farías and others[25] presented a lower estimated k parameter (0.0020) using data from an homogeneously Cabernet Sauvignon vineyard. This implies that at the same GDD, the model proposed by Ortega-Farías and others[25] obtained lower phenology values (between 1 and 4 phenological stages) compared to the model proposed in the present study.

Table 1. Climatic characterization of the three seasons under study by phenological period

Season	Budburst to Flowering	Flowering to Fruit set	Fruit set to Veraison	Veraison to Harvest*	Budburst to Harvest*
2009-10 Season					
Maximum temperature (T_{max},°C)	21.3	28.1	28.3	26.3	25.3
Minimum temperature (T_{min},°C)	6.9	9.7	11.5	9.3	9.1
Relative humidity (%)	65.3	52.1	53.8	64.6	61.0
Growing degree days (GDD,°C)	253.4	170.8	454.9	472.9	1,352.0
Precipitations (mm)	62.0	0.0	2.8	0.2	65.0
Reference evapotranspiration (ET_0,mm)	225.6	102.8	257.0	228.7	814.1
Water deficit (P- ET_0)	-163.6	-102.8	-254.2	-228.5	-749.1
2010-11 Season	22.6	25.9	27.4	27.0	25.7
Maximum temperature (T_{max},°C)					
Minimum temperature (T_{min},°C)	7.9	6.3	8.3	10.1	9.8
Relative humidity (%)	67.2	56.8	61.1	61.4	62.8
Growing degree days (GDD,°C)	272.5	87.5	459.3	504.7	1,324.0
Precipitations (mm)	44.8	0.0	11.0	30.2	86.0
Reference evapotranspiration (ET_0,mm)	210.9	68.3	267.4	262.0	808.6
Water deficit (P- ET_0)	-166.1	-68.3	-256.4	-231.8	-722.6
2011-12 Season	22.5	27.4	29.4	28.9	26.8
Maximum temperature (T_{max},°C)					
Minimum temperature (T_{min},°C)	7.0	8.9	11.9	11.8	10.0
Relative humidity (%)	64.5	58.2	59.2	59.1	60.8
Growing degree days (GDD,°C)	263.3	105.3	574.2	507.9	1,450.7
Precipitations (mm)	9.0	0.0	0.0	7.0	16.0
Reference evapotranspiration (ET_0,mm)	218.2	75.7	317.6	246.2	857.7
Water deficit (P- ET_0)	-209.2	-75.7	-317.6	-239.2	-841.7

Data obtained from an Automatic Weather Station located at the field trial. *Harvest was performed when the berries reached 22°Brix.

Table 2. Estimated parameter values and goodness of fit of the proposed phenology model in grapevine

Parameter	Estimated	Confidence interval*	SD	MAE	R2
k	0.002864	0.002793 to 0.002934	0.77	0.56	0.99**

*At 95% of confidence. **Significant relationship (*p* value < 0.0001). SD and MAE: expressed as phenological scale units.

Table 3. Validation of the proposed model with data from the experimental vineyards in 2011-12 season, and from commercial vineyards from 2000-01 season

Producer	R^2	EF	SD	MAE
Z1-3	0.99**	0.99	1.10	0.78
Z2-3	0.99**	0.99	1.00	0.76
P1	0.98**	0.96	1.70	1.44
P2	0.98**	0.96	1.84	1.46
P3	0.99**	0.98	1.32	1.03

Z1-3: 2011-2012 season data, zone 1. Z2-3: 2011-2012 season data, zone 2. P1, P2 and P3 correspond to producers. **Significant relationship (*p* value < 0.0001). SD and MAE: expressed as phenological scale units.

A high degree of fit was shown between the phenological stages observed and those estimated by the proposed model with an R^2 value equal to 0.99. **Figure 2** shows that the observed phenology values are positioned very close to the model curve for the 2009-10 and 2010-11 seasons, in both zones of the vineyard quarters. The SD and MAE values were 0.77 and 0.56, respectively, being in both cases lower than one phenological stage. The regression analysis carried out shows that the proposed model is highly significant (*p*-value <0.000).

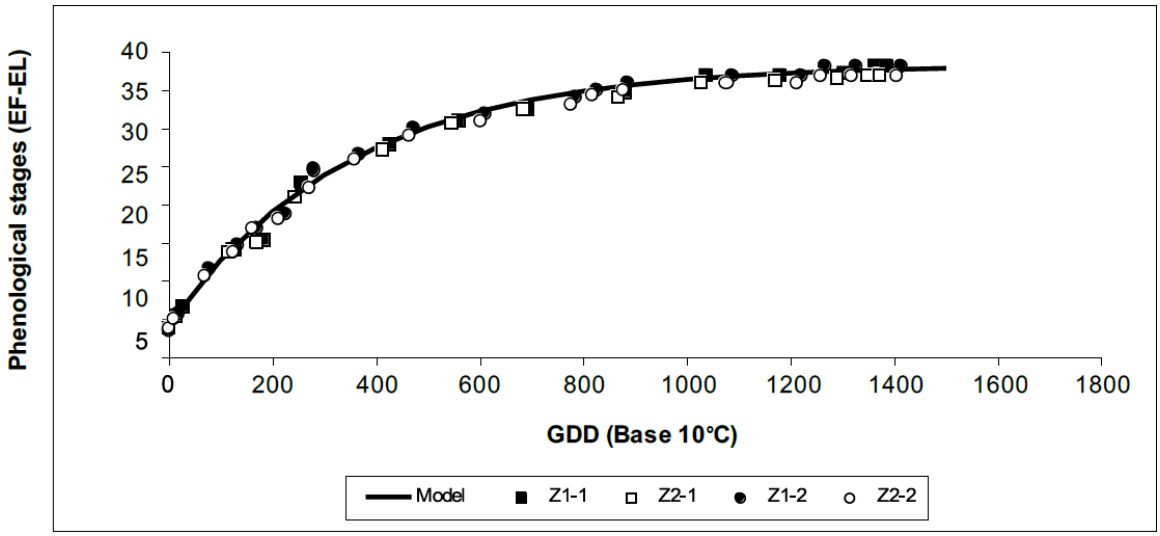

Figure 2. Calibration of the phenology model for Cabernet Sauvignon

Model: Phenology model; Z1-1: 2009-2010 season data, zone 1. Z2-1: 2009-2010 season data, zone 2. Z1-2: Data 2010-2011 season, zone 1. Z2-2: Data 2010-2011 season, zone 2.

The model residuals were normally distributed (Supplementary **Figure S1**), with the greatest differences (greater than 1 phenological stage) occurring at the beginning of the season (approximately at 250 GDD), corresponding to the initial phenological stages of vegetative development of the grapevine (stages 15 and 18 of the phenological scale). This difference between observed and estimated values could be due to the subjectivity of the measurement of the first phenological stages[25].

Figure 2 shows that, within each season, there is a lag in the development of phenology between the two zones of the field, which begins in budburst and extends until harvest, with the greatest differences being observed in flowering (phenological stage 23 of the scale used), which reached 5-6 days. Several authors have proposed predictive models of grapevine development and phenology. Bindi[26] proposed an empirical model based on climatic data describing the development of Cabernet Sauvignon vines growing in Italia, obtaining R^2 values of 0.97. García de Cortázar-Atauri and others[29] proposed a model that predicts the phenological stage

of budburst for Mediterranean climatic conditions in southern France, obtaining a prediction error of 18.3 days (root mean square error). Nendel[30] established a model to predict grapevine budburst for Western European conditions, obtaining a standard deviation of 2.5 days in the prediction. Caffarra and Eccel[31] established 3 models to predict the phenological events of budburst, flowering and veraison in grapevines growing in Italy, obtaining R^2 values of 0.36, 0.79 and 0.69, respectively. Valdés-Gómez and others[32] used the STICS model[29] to simulate the date of occurrence of the main vine phenological stages for vineyards located in France and Chile, obtaining differences of up to 6 days between the observed and estimated values. In Chile, Ortega-Farías and others[25] calibrated a phenology model in Cabernet Sauvignon, similar to this study, obtaining R^2 values equal to 0.97 and SD of 1.62 for the calibration data set. Verdugo-Vásquez and others[33] reported R^2 and MAE values from 0.97 to 0.99 and 1.35 to 1.69 for table grapes varieties, respectively. The prediction variability varied from 4.4 to 19.4 days, obtaining the best results for the flowering period.

3.3 Model Validation

The results of the validation of the proposed phenology model are presented in **Table 3**. There is a high degree of fit between the observed phenology values and those estimated by the model for the four vineyards under study, with R^2 and EF of 0.98 and 0.96, respectively.

The statistical validation indicated a better fit in the experimental vineyards compared to the commercial ones (**Table 3**). This could be explained by two reasons: i) The phenological observation methodology used in the experimental trial considered the average of 30 shoots per plant, while in the commercial vineyard phenology was recorded only in one shoot per plant. This adds an important error in the measurement of phenology given the high variability that exists between shoots of the same plant[34]. ii) Spatial variability of phenology within the experimental vineyards should be considered. This did not occur in the commercial vineyards despite several studies showed a significant spatial variability in variables such as growth, water status, and yield, including phenology, within the vineyard plots[2][4][5][9][15].

The evolution of vine phenology in the two zones of the experimental vineyard during 2011-12 season shows a difference in phenological development between the two zones (**Figure 3**). This difference begins at budburst and continues throughout the vine growing season until harvest, with the greatest differences being observed at flowering (phenological stage 23 of the scale used). This behavior had already been observed in the data used for model calibration, which would demonstrate a certain stability in the differences between both sectors of the vineyard, which could be associated with constant factors between seasons, such as the physical properties of the soil.

The results of the validation for the commercial vineyards showed an adequate prediction of phenology, but it was better for the case of P3 compared to the rest (**Table 3Table 3**; **Figure 3**). These differences could be due to the management characteristics of the vineyards, where P3 has the same conduction system as the one used for the model calibration. The viticulturists of P2 and P1 vineyards trained their vines using an overhead and Scott-Henry trellis system, respectively. This situation would determine differences in the ratio of leaf surface per gram of fruit produced (number of clusters per linear meter and light interception by the foliage), which would have a direct impact on berry maturity, more specifically on sugar accumulation (sugar solids), which is a very important variable in the phenological scale used in this study[35].

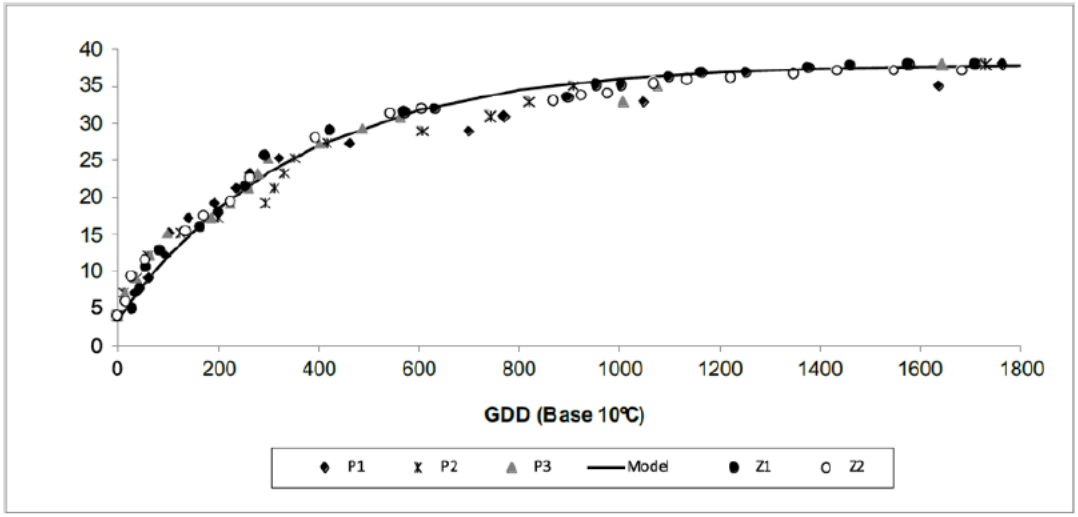

Figure 3. Validation of the phenology model, with data from a plot with high spatial variability of phenology (Z1 and Z2) and with data from plots considered as homogeneous (three commercial vineyards, P1, P2 and P3)

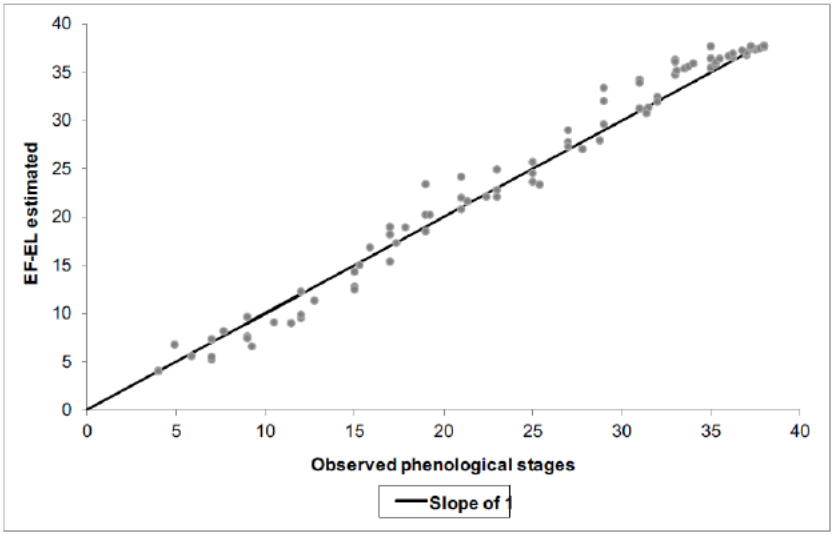

Figure 4. Comparison between observed and estimated values of phenology by the model for the five validated cases (Zone 1 and Zone 2 of high spatial variability, including three commercial vineyards)

The proposed model has a good fit in the three vineyard producers (homogeneous plots), despite the fact that they present differences in conduction system, plant age, orientation and irrigation system. This would indicate that the proposed model can be useful for the prediction of grapevine phenology under conditions of high and low spatial variability of phenology and under different management systems, being a simple model for the Maule Valley area.

Figure 4 shows a comparison between observed and estimated values of phenology by the model for the validated cases. In general, it is observed that there is a high degree of fit between the observed phenology data and those estimated by the model, obtaining an overall R^2 higher than 0.98. In the first phenological stages, related to the vegetative development of the vine (Stage 5 to Stage 15 of the proposed scale), it is observed that the model underestimates the phenology values, while for the phenological stages from flowering (Stage 19) to harvest (Stage 38) a small overestimation by the proposed model is observed.

Despite this, the proposed model presented a high degree of fit between the phenology stages observed and those estimated for Cabernet Sauvignon established in the Maule Valley. The fit was even better than that

reported by other authors in other locations[25]. Furthermore, the model used in this study allows continuous prediction of phenological events (**Figure 2**), which can be used to simulate phenological evolution under climate change scenarios[36].

4. Conclusions

A phenological model was proposed as a function of the daily thermal sum, which was elaborated based on the monomolecular Mitscherlich equation. In the calibration process, a value of 0.0028 was obtained for the k parameter and the proposed model presented a high degree of fit between the estimated and observed phenological stages (R^2=0.99, SD=0.77 and MAE=0.56). The indicators of statistical validation for the two contrasting zones of the experimental plot were better than those obtained from the commercial vineyards, which could be explained by two reasons: i) a more precise phenological sampling methodology was used in the experimental vineyard compared to the commercial ones, and ii) the inclusion of the spatial variability effect of phenology within the experimental vineyard. The correct behavior of the model in all the situations evaluated in this study would indicate that it can be useful for the prediction of the phenology of Cabernet Sauvignon grapevines under conditions of high and low spatial variability of phenology and under different management systems in the Maule Valley area. Despite this, the model could be supported with more studies regarding different productive zones in the Maule Valley.

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Transparency of data

Data not available: The data set that supports the results of this study is not publicly available.

Author contribution statement

	Verdugo-Vásquez N	Gutiérrez-Gamboa G	Valdés-Gómez H	Acevedo-Opazo C
Conceptualization	■		■	■
Data curation	■			
Investigation	■	■		
Supervision			■	■
Writing – original draft	■	■		
Writing – review and editing	■	■		

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Supplementary Material

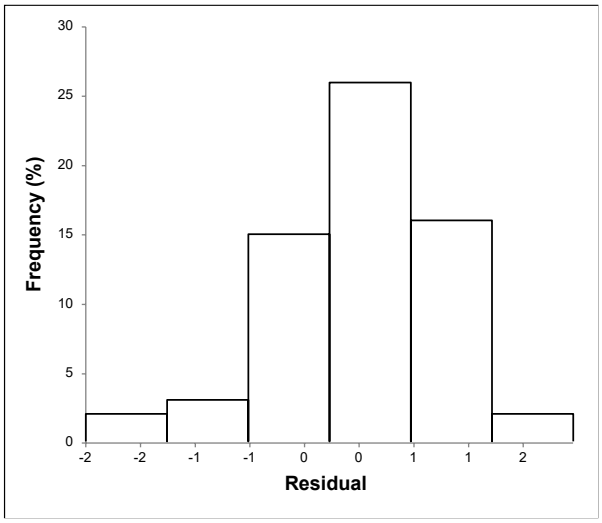

Figure S1. Comparison between observed and estimated values of phenology by the model for the five validated cases (Zone 1 and Zone 2 of high spatial variability, including three commercial vineyards)