

Model development to predict phenological scales of table grapes (cvs. Thompson, Crimson and Superior Seedless and Red Globe) using growing degree days

Nicolas Verdugo-Vásquez, Carolina Pañitrur-De la Fuente and Samuel Ortega-Farías*

Universidad de Talca, Facultad de Ciencias Agrarias, CITRA, 2 Norte, 685 Talca, Chile

Abstract

Phenological models have been made mainly for winegrape cultivars, despite the economic importance of table grapes. The aim of this work was to develop and validate models for predicting phenological scales of table grapes (cvs. Thompson, Crimson and Superior Seedless and Red Globe) grown under semi-arid conditions. Measurements of phenology were carried out weekly from budburst to harvest during four growing seasons (2009-2013). Phenology models were developed using the Mitscherlich monomolecular equation where the dependent and independent variables were the Eichhorn and Lorenz phenological (ELP) scale modified by Coombe and the growing degree days (GDD), respectively. Results indicated that there were strong non-linear correlations between the ELP scale and GDD for the four cultivars with coefficient of determinations (R^2) ranging between 0.97-0.99. Also, validation indicated that the models were able to predict ELP scale with a root mean square (RMSE) and mean absolute error (MAE) ranging between 2.1-2.4 and 1.35-1.69, respectively. The prediction variability (expressed in days) was between 4.4-19.4 days, obtaining the best results for the flowering period. This study suggested that the phenological models based on GDD could be useful planning tools for farming, especially from budburst to veraison of table grape cultivars.

Keywords: growth model, bio-mathematical models, phenology, growth stages, *Vitis vinifera*

manuscript received 9th Mars 2017 - accepted 6th April 2017

doi:10.20870/oeno-one.2017.51.2.1833

Introduction

Phenology, which studies the succession of plant growth stages, is important at different spatial scales (Mullins *et al.*, 1992; Jones and Davis, 2000; Verdugo-Vásquez *et al.*, 2016). For example, at the regional level, characterization of phenology determines crop varieties that are more adapted to specific climate conditions (Ortega-Farías *et al.*, 2002; Piña and Bautista, 2004; Zavalloni *et al.*, 2006; Gris *et al.*, 2010; Santos *et al.*, 2011; Fernández-González *et al.*, 2013). At farm scale, the estimation of the phenological stages is important for crop management practices such as irrigation, fertilization, pesticide spraying and harvest planning (Mullins *et al.*, 1992; Ortega-Farías *et al.*, 2002; Zavalloni *et al.*, 2006; Fernandez-Gonzalez *et al.*, 2011). Recently, the study of crop phenology has been used to evaluate the effect of climate change on viticulture (Marta *et al.*, 2010; Caffarra and Eccel, 2010, 2011; Moriondo *et al.*, 2011). These studies have established changes in vine phenology in the coming years under different greenhouse gas emission scenarios defined by the Intergovernmental Panel on Climate Change (IPCC).

The main factor that affects the occurrence of phenological stages is air temperature (García de Cortázar-Atauri *et al.*, 2009; Chuine *et al.*, 2013; Miranda *et al.*, 2013), which is expressed primarily as heat accumulation or growing degree days index (GDD). Therefore, phenological models usually relate the timing of phenological events (i.e. budburst, flowering) to temperature expressed as GDD. Using GDD, predictive models of phenology have been developed for various fruit trees located in different geographical areas. For example, Zavalloni *et al.* (2006) developed a predictive model of flowering for *Prunus cerasus* located in Michigan, USA, as a tool to optimize and improve disease control, fertilization and irrigation management. Miranda *et al.* (2013) developed predictive models of phenology for *Prunus persica* located in the valleys of Guadiana and Ebro (Spain) to estimate the phenology under different climate conditions, including future climate scenarios. Chmielewski *et al.* (2011) developed a predictive model for *Malus domestica* in Germany, with the aim of studying the impact of climate change. For *Vitis vinifera*, several authors have generated predictive models for phenology, either as management tools (Williams *et al.*, 1985a and b; Ortega-Farías *et al.*, 2002; Valdés-Gómez *et al.*, 2009; Mariani *et al.*, 2013; Cola *et al.*, 2014; Molitor *et al.*, 2014b; Santibáñez *et al.*, 2014) or to assess the potential impact of climate change effects in different grape productive areas of the world (Webb *et al.*, 2007; Caffarra and Eccel, 2010;

Jorquera-Fontena and Orrego-Verdugo, 2010; Marta *et al.*, 2010; Moriondo *et al.*, 2011; Fila *et al.*, 2012). A summary of the mechanisms used for the development of predictive models can be found in Chuine *et al.* (2013). Of the researchers mentioned above only Williams *et al.* (1985a and b) and Santibáñez *et al.* (2014) worked with table grape cultivars, located in USA and Chile, respectively.

For *Vitis vinifera*, there are specific phenological models to predict a limited number of plant growth stages, such as budburst, flowering or veraison (García de Cortázar-Atauri *et al.*, 2009, Caffarra and Eccel, 2010; Parker *et al.*, 2011), while others were developed to predict the entire phenological development of grapevine (from budburst to harvest), which are important for the application of pesticides during vegetative growth or flowering onset (Ortega-Farías *et al.*, 2002; Fernandez-Gonzalez *et al.*, 2011; Fernández-González *et al.*, 2013; Molitor *et al.*, 2014b). In both approaches, phenological scales are used to develop bio-mathematical models in which phenology is incorporated as a quantitative variable, assigning to each phenological event a number or code. Examples of phenological scales used in *Vitis vinifera* correspond to the scales proposed by Meier (2001) and Coombe (1995).

Chile is one of the main producers and exporters of table grapes, supplying 23 % of world imports. Total area planted with table grapes represents 20 % of the fruit area of Chile, with 52,926 hectares (ODEPA 2010). The production area is distributed from the Atacama Region to the Maule Region. The O'Higgins Region has the largest planted area (25.6 %), where cultivars Thompson, Crimson and Superior Seedless and Red Globe are the most important (ODEPA, 2010). The aim of this work was to develop and validate phenological models for four cultivars of table grapes (Thompson, Crimson and Superior Seedless and Red Globe) grown under semi-arid conditions.

Materials and Methods

1. Study area and cultivars

To develop phenological models for four cultivars of table grapes (Thompson, Crimson and Superior Seedless and Red Globe), the phenological data were collected from drip-irrigated commercial table grape vineyards, located in Peralillo, O'Higgins Region, Chile (34°25'58''S, 71°31'57''W, 140 m.a.s.l.), during four growing seasons (2009-2013). Details of area, year of plantation, rootstock, soil type, irrigation system and trellis for each cultivar are presented in Table 1. This region is characterized by

Table 1. Main field characteristics of the table grape experimental fields.

Cultivars	Number of fields (n)	Area (ha)	Year of plantation	Rootstock	Soil type and texture	Irrigation system	Trellis	Spacing (m x m)
Thompson Seedless	9	25.66	2005	Own-rooted	Mancuman (sandy loam)	Drip	Overhead horizontal (Pergola)	3.2 x 2.8
Crimson Seedless	8	26.29	2005	Own-rooted	Mancuman (sandy loam)	Drip	Overhead horizontal (Pergola)	3 x 3.5
Red Globe	6	18.04	2009	Thompson	Mancuman (sandy loam)	Drip	Overhead horizontal (Pergola)	3.2 x 2.8
Superior Seedless	3	7.41	2010	Thompson	Mancuman (sandy loam)	Drip	Overhead horizontal (Pergola)	3.2 x 2.8

Table 2. Summary of the Eichhorn and Lorenz phenological scale modified by Coombe (1995).

Phenological scale (ELP)	Phenological stage
1	Winter bud
4	Green tip, first leaf tissue visible
7	First leaf separated from shoot tip
12	5 leaves separated; shoots about 10 cm long; inflorescence clear
17	12 leaves separated; inflorescence well developed; single flowers separated
23	17-20 leaves separated; 50% caps off, full bloom
26	Cap-fall complete
27	Setting; young berries enlarging (> 2 mm diam.), bunches at right angles to stem
31	Berries pea-size (7 mm diam.)
32	Beginning of bunch closure, berries touching (if bunches are tight)
33	Berries still hard and green
35	Berries begin to colour and enlarge: veraison
38	Berries harvest-ripe (22°Brix)
39	Berries over-ripe
41	After harvest: cane maturation complete
43	Beginning of leaf fall
47	End of leaf fall

ELP: Eichhorn and Lorenz phenological scale

Mediterranean climatic conditions, with mean maximum temperatures of 27.9 °C and a mean minimum of 4.1 °C, reached during the months of January and July, respectively. Annual rainfall is about 495 mm, concentrated between April and October. The soil corresponds to the Mancuman series, which is characterized by colluvial soils, sandy loam, thin to moderately deep, good drainage, with slopes between 2-15 %

An automatic weather station (Davis, model Vantage, USA) installed next to the fields was used to measure air temperature at 15 min intervals. This information was used to estimate the GDD from budburst to harvest of each cultivar during the four seasons. Additionally, rainfall data were obtained from the

platform of “Dirección General de Aguas” of Chile (www.dga.cl).

2. Model development and calibration

To develop the models, measurements of phenology stages of each cultivar were carried out in 22 plants/ha. Phenological growth stages were evaluated using the Eichhorn and Lorenz phenological (ELP) scale modified by Coombe (1995). Table 2 indicates the main phenological stages associated to ELP scale, allowing the phenology to be entered as a quantitative variable in mathematical models (Ortega-Farí (Ortega-Farías *et al.*, 2002; Fernández-González *et al.*, 2013). In this study, phenological stages were measured weekly from budburst (ELP 4) to harvest (ELP 38). The harvest date (ELP 38) was

considered by the producer, based on technical and commercial parameters. The total soluble solids ($^{\circ}\text{Brix}$) were the principal commercial parameters used to define harvest date. For cv. Red Globe and Crimson 17 $^{\circ}\text{Brix}$ was defined for harvest date, while for cv. Thompson it was 16 $^{\circ}\text{Brix}$ and for cv. Superior it was 15.5 $^{\circ}\text{Brix}$.

Development of phenology models was based on the methodology proposed by Ortega-Farías *et al.*, (2002), who estimated the ELP scales of grapevines (Cabernet-Sauvignon and Chardonnay cultivars) as a function of GDD using the Mitscherlich monomolecular equation (Thornley and Johnson 1990):

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

where: W corresponds to the ELP stage; W_f corresponds to harvest (ELP=38); W_0 corresponds to budburst (ELP=4); k corresponds to the rate of phenological development; and t corresponds to GDD ($^{\circ}\text{Cd}^{-1}$). The GDD were estimated from budburst to harvest as follows (Bindi *et al.*, 1997):

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

where: T_{xi} is the mean daily temperature ($^{\circ}\text{C}$) and T_u is the threshold temperature (10°C) (Mullins *et al.*, 1992). The k parameter of Eq. 1 was determined using the “Curve Fitting Toolbox” tool from Matlab© Software, which optimizes the parameter value using the technique of least squares (mathematical techniques) (Caffarra and Eccel, 2010; Chuine *et al.*, 2013).

This approach allows the prediction of the phenological events of table grapes from budburst (the growth stage of budburst must be measured in the field) to harvest. Therefore, only the effect of thermal accumulation is considered in this approach (García de Cortázar-Atauri *et al.*, 2009, Caffarra and Eccel, 2010). For model development, a non-linear regression analysis between ELP scales and GDD was done for the four cultivars. Details of the seasons

that were used to develop and validate predictive phenological models are presented in Table 3. For model calibration, the mean absolute error (MAE) and the root mean square error (RMSE) were used to characterize the accuracy of the model. Values of MAE and RMSE were estimated as follows (Mayer and Butler, 1993):

$$\text{MAE} = \frac{\sum_{i=1}^n |y_{obs} - y_{sim}|}{n} \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (y_{obs} - y_{sim})^2}{n}} \quad (4)$$

where: y_{obs} is the observed value of ELP scale; Y_{sim} is the predicted value of ELP scale; and n is the number of observations.

3. Model external validation

Model external validation was performed using independent databases as indicated in Table 3 (Validation seasons). Model external validation was carried out using the ratio of estimated to observed values of ELP scale (b), MAE, RMSE and model efficiency (EF). The student's t-test analysis was applied to check whether b was significantly different from unity at the 95% confidence level. Values of MAE and RMSE were estimated using Eq. 3 and 4, respectively, while EF was estimated as follows (Mayer and Butler, 1993):

$$\text{EF} = 1 - \frac{\sum_{i=1}^n (y_{obs} - y_{sim})^2}{\sum_{i=1}^n (y_{obs} - y_{mean\ obs})^2} \quad (5)$$

where: y_{obs} is the observed value of ELP scale; Y_{sim} is the predicted value of ELP scale; $Y_{mean\ obs}$ is the mean value of observed ELP; and n is the number of observations.

Additionally, with the developed models for each cultivar, the GDD necessary to reach the main phenological stages of table grapes studied were determined. Using the information above, the date of occurrence of the phenological stages was estimated (simulated date) and compared with the observed

Table 3. Database used to develop and externally validate the phenological models.

Cultivars	Seasons	
	Development	Validation
Thompson Seedless	2009-2010, 2010-2011	2011-2012, 2012-2013
Crimson Seedless	2009-2010, 2010-2011	2011-2012, 2012-2013
Red Globe	2010-2011, 2011-2012	2012-2013
Superior Seedless	2011-2012	2012-2013

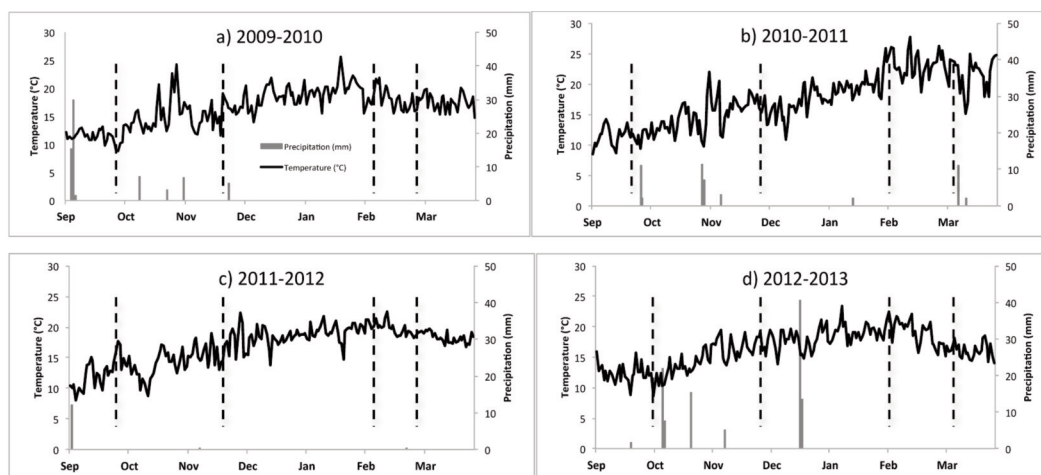


Figure 1. Daily mean temperature (°C) and rainfall (mm H₂O) during the 2009-2010, 2010-2011, 2011-2012 and 2012-2013 growing seasons.

dates, obtaining the errors of prediction expressed in days. For this analysis, data from validation seasons (Table 3) were used. Moreover, an analysis was also done by phenological period, considering four specific periods: (i) Shoot development (ELP 5 to ELP 18), (ii) Flowering (ELP 19 to ELP 26), (iii) Berry development (ELP 27 to ELP 33) and (iv) Ripening (ELP 34 to ELP 38). These phenological periods were chosen because in each of them different vegetative organs are observed. For example, for shoot development the leaves are observed, whereas for berry development clusters are observed. On the other hand, these phenological periods are associated with different labors performed in the fields. For example, the flowering period is related to pesticide spraying, while the ripening period is associated with determining the optimal harvest time.

Results

1. Climatic characterization of the seasons studied

Figure 1 indicates that similar climatic conditions were observed during the four growing seasons (from September to March). For these seasons, the daily mean temperatures were above 10°C, which is considered the threshold temperature of *Vitis vinifera* as indicated by several authors (Mullins *et al.*, 1992; Ortega-Farías *et al.*, 2002; Valdés-Gómez *et al.*, 2009). The average air temperature during the growing seasons ranged between 16.4-17.5°C, with maximum values observed in the 2010-2011 growing season. However, a greater variability of precipitation was observed during the studied periods, with minimum and maximum values of 12.9 mm (2011-2012 season) and 105.5 mm (2012-2013 season),

respectively. Also, precipitation events were concentrated between September and December only in the 2012-2013 season.

Vertical dashed lines represent the average dates of phenological stages considering all cultivars together: budburst, flowering, veraison and harvest, respectively.

2. Development of phenological models for table grapes

Table 4 indicates that there were significant non-linear correlations (Figure 2) between ELP scale and GDD for the four cultivars with R² values ranging between 0.97-0.99. Also, values of k varied between 0.003167 and 0.0042, indicating that each cultivar has a specific rate of phenological development based on GDD. In this regard, García de Cortázar-Atauri *et al.* (2009) observed that the cultivar has a significant effect on the empirical parameter values of phenological models. The above was also observed for table grapes, where Santibáñez *et al.* (2014) showed that cultivars have different development rates depending on precocity, which seems to have a strong genetic control. For grapevines, Fernández-González *et al.* (2013) in Spain and Ortega-Farías *et al.* (2002) in Chile found values of k ranging between 0.00204-0.00226 and 0.0026-0.0032, respectively.

** highly significant (p value<0.05). RMSE and MAE expressed in units of phenological scale. RMSE: Root mean square error, MAE: Mean absolute error.

Additionally, values of MAE were between 1.10-1.54 while those of RMSE ranged between 1.52-

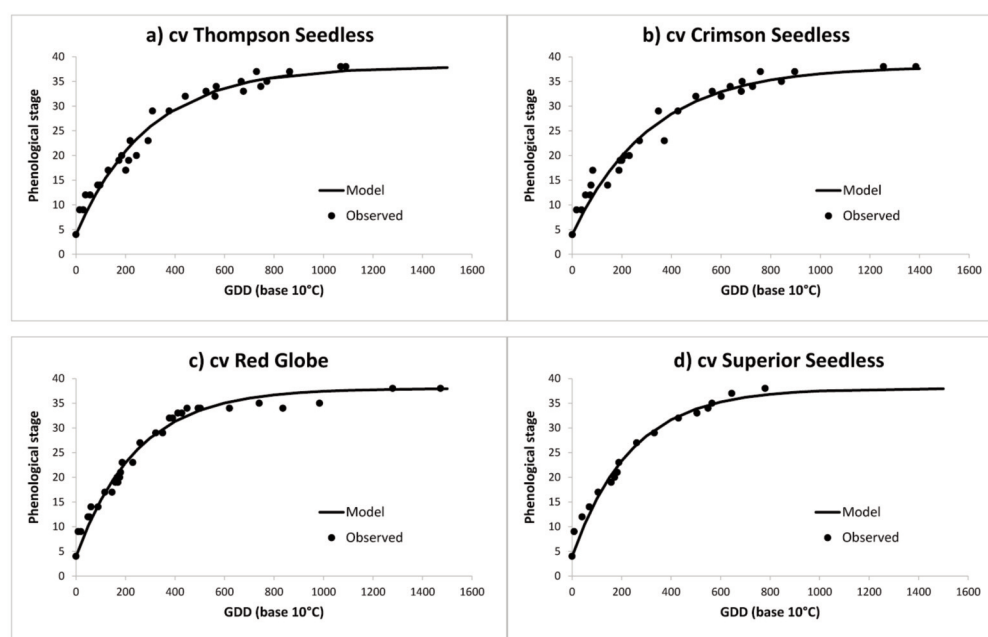


Figure 2. Calibration of table grape phenology models.
a) Thompson Seedless, b) Crimson Seedless, c) Red Globe and d) Superior Seedless.

Table 4. Estimation of k values and statistical parameters for the phenological models of four table grape cultivars (Model Development).

Cultivars	Value of parameter k	95% Confidence interval	R ²	RMSE	MAE
Thompson Seedless	0.003432	0.003152 to 0.003711	0.97**	1.81	1.48
Crimson Seedless	0.003167	0.002910 to 0.003424	0.97**	1.89	1.54
Red Globe	0.004074	0.003830 to 0.004317	0.98**	1.52	1.23
Superior Seedless	0.004200	0.003824 to 0.004575	0.99**	1.55	1.10

1.89. Results of this study were similar to those reported by Ortega-Farías *et al.* (2002) in Chile, who obtained errors between 1.62-2.21 phenological stages for models developed for cultivars Cabernet-Sauvignon and Chardonnay. Moreover, Fernández-González *et al.* (2013) in Spain reported that a model for two grapevine cultivars (Treixadura and Godello) predicted with errors smaller than 2 phenological stages.

Each point on the graph represents the average observed phenological stage of 22 plants/ha. The solid line represents the estimated model for each cultivar. Axis y expressed in units of Eichhorn and Lorenz phenological scale (ELP).

Figure 2 shows the non-linear correlations between ELP and GDD. It is observed that there is a high fit between the proposed model and the observed values of the phenological scale, considering the stages of shoot development (ELP 5 to ELP 18), flowering (ELP 19 to ELP 26), berry development (ELP 27 to

ELP 33) and ripening (ELP 34 to ELP 38). Fernández-González *et al.* (2013) and Ortega-Farías *et al.* (2002) indicated that phenology models presented the best and worst performance for the ripening process and initial stages of growth (shoot development and flowering), respectively. Thus, it is demonstrated that the methods used to develop phenological models in grapevines can be used in table grape cultivars, taking into account that the adjusted parameters are specific for each cultivar and location.

3. Validation of phenology models for table grapes

For model validation, Table 5 indicates that there was a good agreement between observed and estimated values of ELP scale, with EF values ranging between 0.94-0.96. Also, RMSE ranged between 2.1-2.4 and MAE fluctuated between 1.35-1.69, indicating a predicting variability of 2 phenological stages.

Table 5. Main statistics obtained by the external model validation process.

Cultivar	RMSE	MAE	EF	Lineal Regression (Test T)	
				Slope ^x	Intercept ^y
Thompson Seedless	2.1	1.67	0.96	1.01ns	-0.77ns
Crimson Seedless	2.4	1.69	0.94	1.06ns	-2.65**
Red Globe	2.3	1.44	0.95	0.97ns	2.15*
Superior Seedless	2.1	1.35	0.95	0.98ns	2.07ns

Significance: ns: Not significant; *: Significant; **: Highly significant (p value<0.05).

^xH₀:Slope=1; ^yH₀:Intercept=0. RMSE: Root mean square error, MAE: Mean absolute error

and EF: Model efficiency. RMSE and MAE expressed in units of phenological scale.

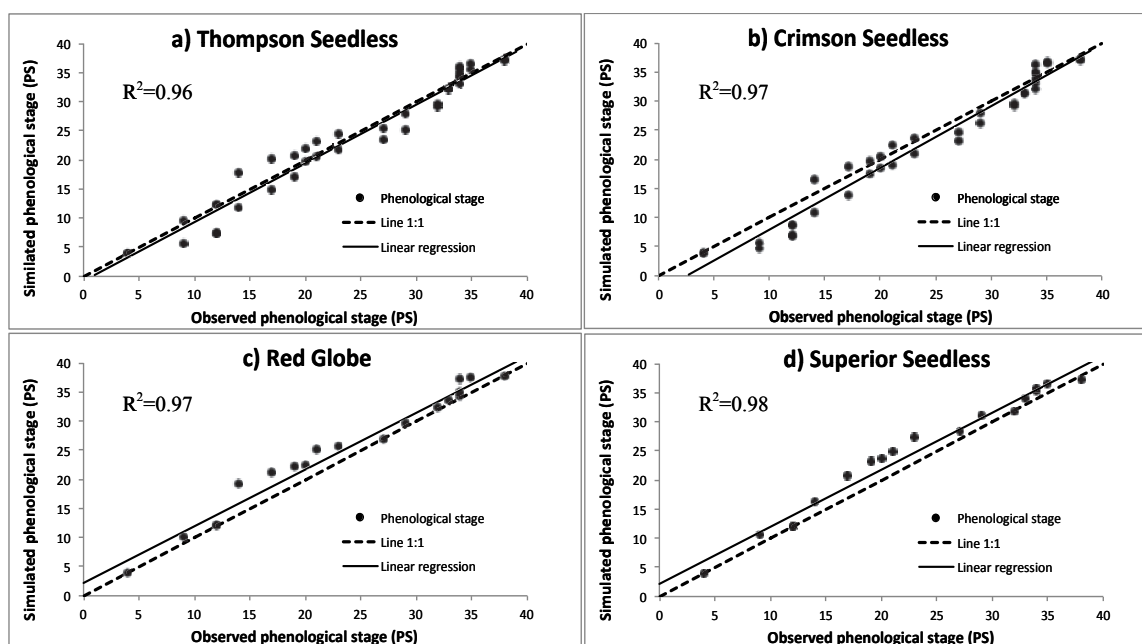


Figure 3. Validation of table grape phenology models. a) Thompson Seedless, b) Crimson Seedless, c) Red Globe and d) Superior Seedless.

With respect to the possible underestimation or overestimation of the phenological models, Table 5 and Figure 3 show the linear regression analysis between the observed and estimated values of ELP scale along with the significance of the test-Z for the slope and intercept. For the four models proposed, the slope was statistically equal to 1 (p value>0.05), indicating that estimated and observed ELP scales were similar (values are around 1:1 line in Figure 3). With regard to intercept, the intercept was statistically equal to 0 only for the models of cvs. Thompson Seedless and Superior Seedless, indicating that the linear regression passed through the origin without existing deviations from the predictions of phenology. By contrast, for the models of cvs. Crimson Seedless and Red Globe, the intercept was statistically different from 0, and there was a deviation in the estimated phenology values (Figure 3). The high degree of adjustment observed may be associated

with the similarity of environmental conditions observed in the growing seasons of the study (Figure 1).

Overall, the development and validation of the four phenological models proposed showed high values of R² and EF with RMSE and MAE near 2 ELP scales, indicating that they can be a useful tool for predicting phenological stages of table grapes. Additionally, the proposed models predict phenological events continuously (Figure 2) using only temperature data, which implies that the proposed models can be used for simulation of phenological evolution under climate change scenarios (Jorquera-Fontena and Orrego-Verdugo, 2010).

Using the proposed models, the GDD necessary to reach the main phenological stages of the four studied table grape cultivars are indicated in Table 6.

Table 6. Comparison between estimated (Pm) and observed (Mean) values of growing degree days (GDD) necessary to reach the main phenological stages for the four table grape cultivars.

Phenological stage	Growing degree days (GDD)											
	Thompson Seedless			Crimson Seedless			Red Globe			Superior Seedless		
	Pm	Mean	SD	Pm	Mean	SD	Pm	Mean	SD	Pm	Mean	SD
Flowering (23 ELP)	238	247	38	258	283	64	200	222	32	194	231	60
Setting (27 ELP)	380	330	42	410	372	41	323	338	14	315	353	30
Veraison (35 ELP)	707	778	107	767	887	156	620	915	152	578	642	108
Harvest (38 ELP)	1210	1060	32	1310	1237	111	1050	1313	145	1010	848	95

Pm = GDD estimated by the phenological models; Mean = mean values of GDD observed, using the growing seasons available; SD = standard deviation of GDD observed, using all growing seasons available, Note = GDD were accumulated from budburst. ELP: Eichhorn and Lorenz phenological scale.

Table 7. Mean absolute error (MAE, expressed in days) to predict phenological stages, classified by phenological period (using external validation data). Results are shown individually for each cultivar and all together.

Phenological period	Cultivar	Number of observations (n)	MAE (days)
Shoot development (ELP 5 to 18)	Thompson Seedless	8	3.9
	Crimson Seedless	8	6.2
	Red Globe	4	4.2
	Superior Seedless	4	5.0
	All cultivars	24	4.8
Flowering (ELP 19 to 26)	Thompson Seedless	8	2.5
	Crimson Seedless	8	2.1
	Red Globe	4	7.0
	Superior Seedless	4	8.8
	All cultivars	24	4.4
Berry development (ELP 27 to 33)	Thompson Seedless	8	5.9
	Crimson Seedless	8	7.9
	Red Globe	5	1.8
	Superior Seedless	5	6.2
	All cultivars	26	5.6
Ripening (ELP 34 to 38)	Thompson Seedless	4	16.5
	Crimson Seedless	4	21.6
	Red Globe	2	31.1
	Superior Seedless	2	9.0
	All cultivars	12	19.4

ELP: Eichhorn and Lorenz phenological scale.

It is observed that the GDD ranged between 1010-1310 GDD to reach harvest (accumulated from budburst), with cvs. Red Globe and Superior Seedless having the lowest thermal requirements (expressed in GDD). The standard deviation (SD) values in Table 6 represent the inter-annual variability for the GDD observed. The phenological stages of veraison (ELP 35) and harvest (ELP 38) presented the highest inter-annual variability (highest SD values). This may be due to the fact that these phenological stages are difficult to identify, increasing variability due to the different evaluations done by the people involved in the measurements

(Molitor *et al.*, 2014b). On the other hand, the greatest differences between observed (Mean) and estimated values (Pm) of GDD were found for the phenological stages of veraison (ELP 35) and harvest (ELP 38). The above differences may be due to the shape of the proposed model. From phenological stage 33 (ELP), the curve is asymptote; therefore, the response of the phenological scale to the GDD is less sensitive. On the other hand, there may be other factors that affect the stage of veraison and harvest, such as the leaf area to fruit mass ratio (Parker *et al.*, 2014).

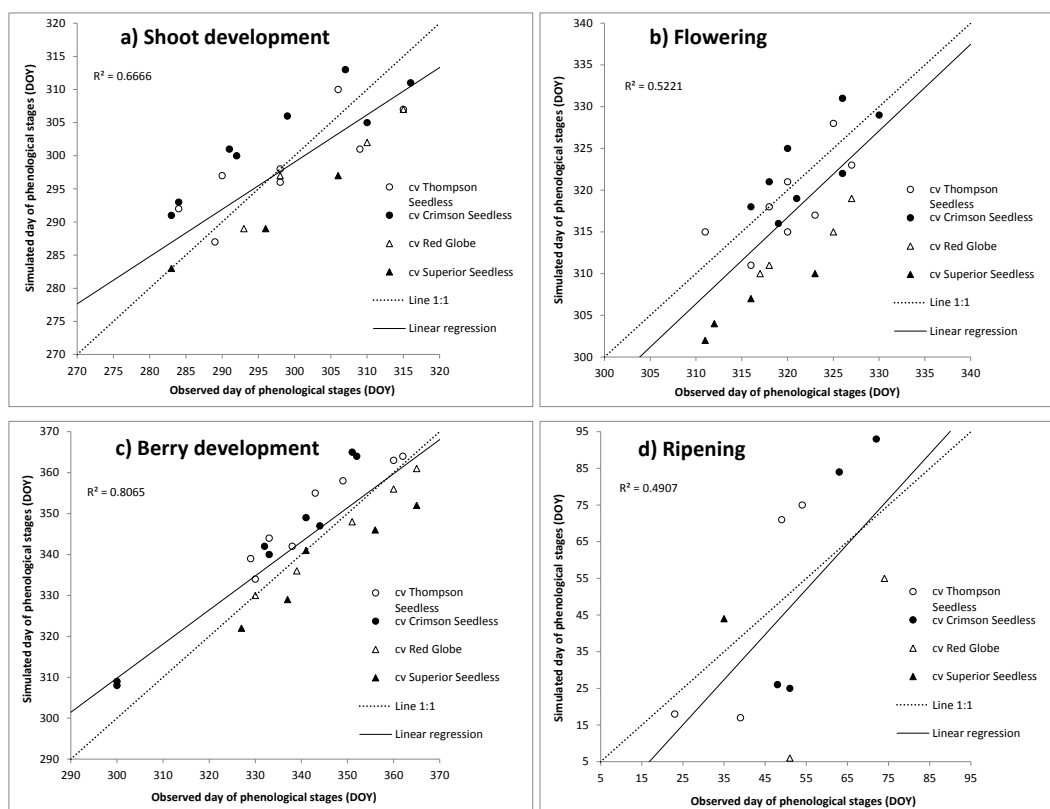


Figure 4. Predicted and observed dates of phenological stages for all cultivars, classified by phenological period.

a) Shoot development (ELP 5 to ELP 18), b) Flowering (ELP 19 to ELP 26),

c) Berry development (ELP 27 to ELP 33) and d) Ripening (ELP 34 to ELP 38).

Each point represents the day of year (DOY) for a given observed/predicted phenological stages.

ELP: Eichhorn and Lorenz phenological scale.

For grapevines, Ortega-Farías *et al.* (2002) described that Cabernet-Sauvignon and Chardonnay required about 1558 and 1275 GDD from budburst to harvest, respectively. For table grapes, Williams *et al.* (1985a) reported a thermal accumulation between 1611-2007 to reach harvest for the cv. Thompson Seedless growing in different locations in the San Joaquin Valley (California, USA). The differences of GDD needed to reach harvest can be attributed to (i) the methodology used to estimate the onset of thermal accumulation; for example, Williams *et al.* (1985a) used a fixed calendar date, whose determination was based on historical observation (20 years) of budburst of Thompson Seedless cultivars, (ii) the definition of harvest time; in this work the total soluble solids ranged between 15.53-17.2°Brix while those observed by Williams *et al.* (1985a) were between 20-21.5°Brix, and (iii) different soil and climatic conditions (Williams *et al.*, 1985a and b).

From a practical and operational point of view, it is essential to determine the accuracy of the models in terms of days, as it is the time unit used to plan all sort of agricultural operations. To perform this validation, the GDD values necessary to reach the

main phenological stages (Table 6) and the measured climate data were used to estimate the predicted date of occurrence of the phenological stage (Table 7 and Figure 4).

The phenological stages are grouped into four major periods (Figure 4), and the information is presented together for the four cultivars under study. R^2 values ranged between 0.49 and 0.81, finding the best results for the periods of shoot development and berry development. It is observed that together the proposed models are able to predict the phenology of table grape cultivars with values of MAE ranging between 4.4-19.4 days (Table 7), obtaining the best results for the flowering period (considering all cultivars together), which had a difference of less than 1 week (4.4 days). Therefore, the models have a high practical applicability, especially for planning the application of plant protection products, where the stages of flowering are more susceptible to fungal diseases such as powdery mildew and botrytis (Campbell *et al.*, 2007, Fernandez-Gonzalez *et al.*, 2011). Similarly, it is observed that values of MAE for shoot and berry development were less than 6 days for almost all the cultivars (Table 7). This

prediction could possibly be used as reference information for planning work associated with these phenological periods (canopy management, fertilization, irrigation scheduling, among others). These results were similar to those observed by Santibáñez *et al.*, (2014), who indicated errors between 2-3 days for the observed and simulated dates of occurrence of the main phenological stages (flowering, fruit set, veraison and harvest) of table grapes. Finally, the worst results were obtained for the ripening period where the MAE was approximately 19 days. This may be for different reasons: (i) during the ripening period, other factors besides temperature could affect this period such as productive handling and the timing of harvest (Valdés-Gómez *et al.*, 2009), (ii) the observed variability between seasons for the phenological stage of veraison and harvest (Table 6, SD), and (iii) the harvest date in this study was determined by the producer based on technical and commercial criteria, increasing variability between seasons for the harvest date (Table 7).

Discussion

In this study a simple but accurate mathematical model based on temperature data expressed as GDD to predict all phenological scales of table grapes grown under semi-arid conditions is proposed. This model obtained good prediction accuracy and had results similar to those observed in studies conducted in grapevine cultivars in different areas (Ortega-Farías *et al.*, 2002; Fernández-González *et al.*, 2013; Molitor *et al.*, 2014b). The implementation of this model only requires the adjustment of one parameter (k , Eq. 1), which is specific for each cultivar, as was observed in Table 4. The proposed methodology values historical information of the phenological stages compiled by the producers, measured by means of easy-to-use phenological scales in the field. On the other hand, this methodology is based on the use of weather information easily accessible (mean daily temperature data); these data are available from meteorological stations or service providers.

This phenology model can help the sustainability of the table grape industry through improved crop management. For example, providing dates for timely irrigation, hormone application, harvest, etc. On the other hand, new strategies to control powdery mildew require in advance the date of occurrence of the phenological stages as key information, with the aim of monitoring the plants and reducing the number of pesticide spraying (Valdés-Gómez *et al.*, 2017). Thus, with this simple model it is possible to predict the different phenological stages of table

grapes, which are key to managing the fields, being one of the main advantages of the methodology presented in this study. However, for the phenological period of ripening, the worst results were observed, with errors of more than 2 weeks. To improve this, we propose including specific models for the ripening of berries, including quality indicators used for programming the harvest of table grapes, such as total soluble solids, titratable acidity and berry diameter (Muñoz-Robredo *et al.*, 2011), as suggested by Ortega-Farías *et al.* (2002) and Fernández-González *et al.* (2013) for grapevines.

On the other hand, it is important to note that the climatic conditions were very similar (Figure 1) for both the calibration and validation seasons. Therefore, the estimation of phenological stages using the proposed model under different climatic conditions to those used to build the models might not be very accurate. Therefore, future studies should evaluate the accuracy of the model under different climatic conditions to determine if it is possible for use under other conditions.

Finally, one of the practical limitations of the model proposed is that it is necessary to know the day of year (starting date) of the phenological stage of budburst (4 ELP) for the accumulation of GDD. The date of occurrence of budburst must be determined by observations performed by producers. An alternative to facilitate the practical application of the proposed model is to predict the date of occurrence of budburst by means of climate models, such as the models developed by García de Cortázar-Atauri *et al.* (2009) or Molitor *et al.* (2014a). In this way, the present model can be directly coupled with budburst models to predict all phenological stages using climatic information, as suggested by Molitor *et al.* (2014b). This latter cooperation of predictive models could be available to both (i) producers, for practical applications and (ii) researchers, for example, to simulate the effects of climate change on the phenology of table grape cultivars.

Conclusion

A simple phenological model for four table grape cultivars (Thompson Seedless, Crimson Seedless, Red Globe and Superior Seedless) was proposed in this study based on accumulated GDD and built using the monomolecular Mitscherlich equation. With regard to prediction accuracy, a high degree of fit between the observed and estimated phenology values was found. The best results were observed for phenological stages related to shoot development, flowering and berry development, with error values

below 6 days. The results suggest that the proposed model can be a useful tool to predict the phenology of these table grape cultivars under similar climatic conditions, helping the sustainability of the table grape industry through improved crop management. Future researchers should evaluate the accuracy of the model under different climatic conditions to determine its possible use under other conditions.

Acknowledgments : The authors of this paper wish to thank PIEI Program of Agricultural Adaptation to Climate Change funded by the Universidad de Talca. The authors would also like to thank the agricultural engineer Roberto Palma for providing phenological data.

References

- Bindi M., Miglietta F., Gozzini B., Orlandini S. and Seghi L., 1997. A simple model for simulation of growth and development in grapevine (*Vitis vinifera* L.). II. Model validation. *Vitis*, 36(2), 73–76.
- Caffarra A. and Eccel E., 2011. Projecting the impacts of climate change on the phenology of grapevine in a mountain area. *Australian Journal of Grape and Wine Research*, 17(1), 52–61. doi:10.1111/j.1755-0238.2010.00118.x
- Caffarra A. and Eccel E., 2010. Increasing the robustness of phenological models for *Vitis vinifera* cv. Chardonnay. *International Journal of Biometeorology*, 54(3), 255–267. doi:10.1007/s00484-009-0277-5
- Campbell P., Bendek C. and Latorre B.A., 2007. Riesgo de oídio (*Erysiphe necator*) de la vid en relación con el desarrollo de los racimos. *Ciencia e Investigación Agraria*, 34(1), 5–11. doi:10.4067/S0718-16202007000100001
- Chmielewski F.-M., Blumel K., Henniges Y., Blanke M., Weber R. and Zoth M., 2011. Phenological models for the beginning of apple blossom in Germany. *Meteorologische Zeitschrift*, 20(5), 487–496. doi:10.1127/0941-2948/2011/0258
- Chuine I., García de Cortazar-Atauri I., Kramer K. and Hänninen H., 2013. Plant development models. In M. D. Schwartz (Ed.), *Phenology: An Integrative Environmental Science* (pp. 275–293). Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-6925-0
- Cola G., Mariani L., Salinari F., Civardi S., Bernizzoni F., Gatti M. and Poni S., 2014. Description and testing of a weather-based model for predicting phenology, canopy development and source–sink balance in *Vitis vinifera* L. cv. Barbera. *Agricultural and Forest Meteorology*, 184, 117–136. doi:10.1016/j.agrformet.2013.09.008
- Coombe B.G., 1995. Adoption of a system for identifying grapevine growth stages. *Australian Journal of Grape and Wine Research*, 1(2), 104–110. doi:10.1111/j.1755-0238.1995.tb00086.x
- Fernández-González M., Rodríguez-Rajo F.J., Escuredo O. and Aira M.J., 2013. Influence of thermal requirement in the aerobiological and phenological behavior of two grapevine varieties. *Aerobiologia*, 29(4), 523–535. doi:10.1007/s10453-013-9302-6
- Fernandez-Gonzalez M., Rodriguez-Rajo F. J., Jato V., Escuredo O. and Aira M.J., 2011. Estimation of yield “Loureira” variety with an aerobiological and phenological model. *Grana*, 50(1), 63–72. doi:10.1080/00173134.2011.561871
- Fila G., Di Lena B., Gardiman M., Storchi P., Tomasi D., Silvestroni O. and Pitacco A., 2012. Calibration and validation of grapevine budburst models using growth-room experiments as data source. *Agricultural and Forest Meteorology*, 160, 69–79. doi:10.1016/j.agrformet.2012.03.003
- García de Cortázar-Atauri I., Brisson N. and Gaudillère J.P., 2009. Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). *International Journal of Biometeorology*, 53(4), 317–326. doi:10.1007/s00484-009-0217-4
- Gris E.F., Burin V. M., Brighenti E., Vieira H. and Bordignon-Luiz M.T., 2010. Phenology and ripening of *Vitis vinifera* L. grape varieties in São Joaquim, southern Brazil: a new South American wine growing region. *Ciencia e Investigación Agraria*, 37(2), 61–75. doi:10.4067/S0718-16202010000200007
- Jones G.V. and Davis R.E., 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *American Journal of Enology and Viticulture*, 51(3), 249–261.
- Jorquera-Fontena E. and Orrego-Verdugo R., 2010. Impact of global warming on the phenology of a variety of grapevine grown in Southern Chile. *Agrociencia*, 44(4), 427–435.
- Mariani L., Alilla R., Cola G., Monte G.D., Epifani C., Puppi G. and Osvaldo F., 2013. IPHEN—a real-time network for phenological monitoring and modelling in Italy. *International Journal of Biometeorology*, 57(6), 881–893. doi:10.1007/s00484-012-0615-x
- Marta A., 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. *The Journal of Agricultural Science*, 148(6), 657–666. doi:10.1017/S0021859610000432
- Mayer D.G. and Butler D.G., 1993. Statistical validation. *Ecological Modelling*, 68(1–2), 21–32. doi:10.1016/0304-3800(93)90105-2
- Meier U., 2001. *Growth Stages of Mono- and Dicotyledonous Plants*. Federal Biological Research Centre for Agriculture and Forestry.

- Miranda C., Santesteban L.G. and Royo J.B., 2013. Evaluation and fitting of models for determining peach phenological stages at a regional scale. *Agricultural and Forest Meteorology*, 178–179, 129–139. doi:10.1016/j.agrformet.2013.04.016
- Molitor D., Caffarra A., Sinigoj P., Pertot I., Hoffmann L. and Junk J., 2014a. Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region. *Australian Journal of Grape and Wine Research*, 20(1), 160–168. doi:10.1111/ajgw.12059
- Molitor D., Junk J., Evers D., Hoffmann L. and Beyer M., 2014b. A high-resolution cumulative degree day-based model to simulate phenological development of grapevine. *American Journal of Enology and Viticulture*, 65(1), 72–80. doi:10.5344/ajev.2013.13066
- Moriondo M., Bindi M., Fagarazzi C., Ferrise R. and Trombi G., 2011. Framework for high-resolution climate change impact assessment on grapevines at a regional scale. *Regional Environmental Change*, 11(3), 553–567. doi:10.1007/s10113-010-0171-z
- Mullins M.G., Bouquet A. and Williams L.E., 1992. *Biology of the Grapevine*. New York, USA: Cambridge University Press. Retrieved from <http://books.google.es/books?id=wnNvmRjfxgQC>
- Muñoz-Robredo P., Robledo P., Manríquez D., Molina R. and Defilippi B.G., 2011. Characterization of sugars and organic acids in commercial varieties of table grapes. *Chilean Journal of Agricultural Research*, 71(3), 2–8. doi:10.4067/S0718-58392011000300017
- ODEPA, 2010. Mercado de la uva de mesa.
- Ortega-Farías S., Lozano P., Moreno Y. and León L., 2002. Development of models for predicting phenology and evolution of maturity in cv. Cabernet-Sauvignon and Chardonnay grapevines. *Agricultura Técnica*, 62(1), 27–37. doi:10.4067/S0365-28072002000100003
- Parker A.K., Hofmann R.W., van Leeuwen C., McLachlan A.R.G. and Trought M.C.T., 2014. Leaf area to fruit mass ratio determines the time of veraison in Sauvignon Blanc and Pinot Noir grapevines. *Australian Journal of Grape and Wine Research*, 20(3), 422–431. doi:10.1111/ajgw.12092
- Parker A.K., García de Cortázar-Atauri I., van Leeuwen C. and Chuine I., 2011. General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Australian Journal of Grape and Wine Research*, 17(2), 206–216. doi:10.1111/j.1755-0238.2011.00140.x
- Piña S. and Bautista D., 2004. Ciclo fenológico de cultivares de vid (*Vitis vinifera* L.) para mesa en condiciones tropicales. *Bioagro*, 16(1), 9–15.
- Santibáñez F., Sierra H. and Santibáñez P., 2014. Degree day model of table grape (*Vitis vinifera* L.) phenology in Mediterranean temperate climates. *International Journal of Science, Environment and Technology*, 3(1), 10–22.
- 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. *International Journal of Biometeorology*, 55(2), 119–131. doi:10.1007/s00484-010-0318-0
- Thornley J.H.M. and Johnson I.R., 1990. *Plant and Crop Modelling*. New York, USA: Oxford University Press.
- Valdés-Gómez H., Araya-Alman M., Pañitru-De la Fuente C., Verdugo-Vásquez N., Lolas M., Acevedo-Opazo C., Gary C. and Calonnec A., 2017. Evaluation of a decision support strategy for the control of powdery mildew (*Erysiphe necator* [Schw.] Burr.) in grapevine in the central region of Chile. *Pest Management Science*, 73(9), 1813–1821. doi:10.1002/ps.4541
- Valdés-Gómez H., Celette F., García de Cortázar-Atauri I., Jara-Rojas F., Ortega-Farías S. and Gary C., 2009. Modelling soil water content and grapevine growth and development with the STICS crop-soil model under two different water management strategies. *Journal International des Sciences de la Vigne et du Vin*, 43(1), 13–28. <http://dx.doi.org/10.20870/oeno-one.2009.43.1.806>
- Verdugo-Vásquez N., Acevedo-Opazo C., Valdés-Gómez H., Araya-Alman M., Ingram B. García de Cortázar-Atauri I. and Tisseyre B., 2016. Spatial variability of phenology in two irrigated grapevine cultivar growing under semi-arid conditions. *Precision Agriculture*, 17(2), 218–245. doi:10.1007/s11119-015-9418-5
- 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. *Australian Journal of Grape and Wine Research*, 13(3), 165–175. doi:10.1111/j.1755-0238.2007.tb00247.x
- Williams D.W., Andris H. L., Beede R.H., Luvisi D.A., Norton M.V.K. and Williams L.E., 1985a. Validation of a model for the growth and development of the Thompson Seedless grapevine. II. Phenology. *American Journal of Enology and Viticulture*, 36(4), 283–289.
- Williams D.W., Williams L.E., Barnett W.W., Kelley K.M. and McKenry M.V., 1985b. Validation of a model for the growth and development of the Thompson Seedless grapevine. I. Vegetative growth and fruit yield. *American Journal of Enology and Viticulture*, 36(4), 275–282.
- Zavalloni C., Andresen J.A. and Flore J.A., 2006. Phenological models of flower bud stages and fruit growth of “Montmorency” sour cherry based on growing degree-day accumulation. *Journal of the American Society for Horticultural Science*, 131(5), 601–607.