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DEGREE DAY MODEL OF TABLE GRAPE (*VITIS VINIFERA* L.) PHENOLOGY IN MEDITERRANEAN TEMPERATE CLIMATES

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Abstract: Vine phenology, like many other cultivated species, is highly determined by temperature and solar radiation. This relationship can be modeled using simple numerical expressions to quantify the effect of these climatic variables upon the development rate. This study validated the concept of thermal time, expressed by the concept of degree-days, for predicting the phenological evolution of several table grape cultivars (*Vitisvinifera* L.). To model vine phenology we used the Mitscherlich monomolecular equation and the Eichorn& Lorenz sequence. Phenology was evaluated for three cultivars throughout the growing season in several sites located in the climatic gradient ranging from a desertic to subhumid climates of Central Chile. Upon comparison, the resulting models for different cultivars showed a high degree of coincidence, especially during the embryogenic phase, which suggest the possibility of using a unique model, adapted to the characteristics of each cultivar.
Keywords: Phenological models, bioclimatic indices, degree-days, physiological time.

Introduction

Several attempts have been made to make numerical representations of phenological sequence, in order to predict the occurrence of biological events in several cultivated species (Baker and Reddy, 2001; Garcia-Mozo et al, 2009; Crepinsek et al, 2006; Duchene et al, 2010; Parker et al 2011, Cola et al, 2014). A comprehensive analysis of phenological models was made by De Cortazar-Atauri et al, 2009, Neldel, 2010. The rate of development of organisms which do not regulate its own temperature depends mainly on the environmental temperature. As such, these organisms have evolved in order to synchronize their development with climatic seasons, by means of an accumulation of thermal units or effective temperature. Considering the strong climatic determinism of vine phenology (Sadras, 2013), a numerical model based on thermal time can be more accurate in predicting the occurrence of phenological events than a simple calendar reference.

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The majority of experimental evaluations of phenological sequence have been made on the basis of accumulated degree days as an expression of thermal time. Mostly, this is due to the simplicity of the calculation and information requirement. In the case of vine, there is experimental evidence to consider a base temperature of 7 to 10 ºC as the lower threshold for degree day calculations (Lebon et al. 2004; Moncur et al. 1989; Morriset al. 1980; Ortega et al. 2002; Williams et al. 1985; Wilson et al.1983, Cola et al., 2014). This bioclimatic index has been widely used in California and in many other places to determine the occurrence of different phenological events, with reliable results (Oliveira 1998, Ortega et al. 2002, Williams et al. 1985, Wilson et al.1983). The use of agrometeorological information and systematic records of the vine development allow for the use of phenological models representing the phenotypic time sequences on the basis of temperature dynamics. Reliable phenological models are useful tools for vineyard management and integrated pest management. They are a usefull tool to predict the harvest time as well as periods of increased sensitivity to pests and diseases attacks.

This work is based on the hypothesis that vine phenology has a strong climatic determinism, which development rate is highly related with temperature. The main objective is to develop and to test a general model describing the evolution of table grape phenophases in several climatic conditions. The study area goes from a subdesertic arid to a subhumid temperate climate, dominated by a Mediterranean type precipitation regime in central Chile.

Material and Methods

We selected three common table grape cultivars grown in Chile: Perlette, Red Globe and Thompson Seedless. Selected evaluation sites consisted of commercial plantations with varietal genuineness, planted on their own foot, five years or older, all in full production, all utilizing drip irrigation systems and in good sanitary condition. Phenological stages were evaluated according to the Eichhorn & Lorenz nomenclature, **ELu** (EEPO/EPPO 1984, Coombe 1995), which describes the key phenological stages such as budding, flowering, veraison, harvest and leaf senescence. The **ELu** scale is easy to use in the field and allows for the use of mathematical models considering the numeric expression proposed for phenological stages (Ortega et al. 2002). Twelve observation sites were selected, going from the border of the Atacama desert, in the Copiapo Valley (27°19' S) to the Aconcagua Valley (32°53' S), in the semiarid Central Zones of Chile, as shown in table 1. Since 1988, the observation zone has hosted an important network of agrometeorological stations corresponding to a national monitoring programme (Regional Information Centers, CRIA). This programme installed a network of automated meteorological stations that provide abundant information for practical uses in this important agriculture zone. The observation orchards were selected for hosting one automated station or being neighbor of one of them.

Phenological records were taken in marked observation blocks that were observed and registered throughout the whole growing season. All selected blocks had the same unlimited irrigation and similar canopy management. Within each block, 20 plants were tagged, in order to have a representative sample observing 95% of confidence, considering variability of observed variable or phenological stage. Phenological records were made during six growing seasons. Observations made during the first three years (2006, 2007 and 2008) were used to develop the model, and those made during the second cycle (2010, 2011 and 2012) were used to validate it. Field protocol included nine varieties, three of which were used to build the model. The spatial distribution of observation sites per cultivar is shown in table 1. Climatic records were taken daily with a time interval of 15 minutes. Time climatic series from observation blocks were processed weekly, in order to calculate daily degree-days, using the simple concept of effective temperature:

$$D_{days} = \sum_{t=1}^{t=96} (t - t_0) * \tau$$

Where **t** was the mean temperature of each time interval (15 minutes) and $\mathbf{t_0}$, the base temperature (10 ℃). τ is the time interval in minutes, as a fraction of a day (15/1440).

To establish phenological sequency we considered the start of each phase to occur when 50% of the plant clearly expressed the phenotypic sign of the stage. Experimental data were used to adjust a Mitscherlich monomolecular equation model, also known as the Mitscherlich growth, assuming that many biological processes are asymptotic to a maximum, representing the stability of the phenomenon. In this case we consider that the end phases of cycle show a desacceleration of the rate of development which is well represented by the Mitscherlich equation (Heinen 1999; Ortega et al. 2002; Thorney et al. 1990). The original equation was modified by including an exponent (**α**) related to cultivar precocity. The expression of this model is:

$$Ph_{stage} = Ph_{final} * (1 - \exp(-K_{shape} * D_{days}))^{\propto}$$

Where $\mathbf{Ph}_{stage}$ = Phenological stage at any time during the life cycle (Eichhorn and Lorenz scale), $\mathbf{Ph}_{final}$ = number corresponding to the last modeled phenological stage, $\mathbf{K}_{shape}$ = shape parameter depending on the species, **α** = precocity number. The model fit well between budburst and berries harvest-ripe. After harvest, plants enter in a different phenologic dynamics were minimum temperature play an important role in precipitating the end of the cycle.

This formula assumes that development is a continuous transition from one phase to the next, which represent well the phenological progression of any plant species (Heinen 1999; Ortega et al. 2002; Thorney et al. 1990). Each phenological phase is completed when a genetically defined threshold of temperature summation is achived (Cola et al, 2014). To fit the model we used the Curv Expert software (version 1.3) © 1995-1997 Daniels Hyams. The model was fitted using the 49 observation sites distributed between the 12 localities and cultivars. Each observation site consisted in tagged plants that were used to document the phenological progression of each cultivar. A general model to represent the phenological progression of each cultivar was created by integrating the information gathered at all sites where that given cultivar was registered.

To test the model we used a new set of observation made in 8 different orchards belonging to the same geographic region. The test phase included three varieties: Flame seedless, Red globe and Thomson seedless. Four main pheno phases were monitored during the season 2010, 2011, 2012: full blossom, fruit set, veraison and harvest maturity. The test orchards had the same characteristics of those used for model development.

Table 1. Spatial distribution of observation sites

	Observation blocks number											
	Copiapovalleysites*						**Huascovalleysites***					**Aconcagua valleysite***
Cultivar	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Perlette			2									
Sugraone		1			1			1			1	1
Flame Seedless		1		1		1	3	1		1		1
Regal Seedless		1										1
Thompson Seedless		1	2	1	1	2					1	1
Automn Royal		1										2
Princess		1										1
Redglobe	1	1				2		1	1			1

Crimson Seedless						1						1
*Note: Site 1, Los Loros 1; Site 2, Los Loros 2; Site 3, Los Loros 3; Site 4, Los Loros 4; Site 5, Amolanita; Site 6, Bramador; Site 7, Conay 1; Site 8, Conay 2; Site 9, El Tránsito 1; Site 10: El Tránsito 2; Site11, El Tránsito 3; Site 12, Calle Larga.												

Results and Discussion

Model Development

Table grape phenology showed the same climatic determinism in all experimental sites. Time from bud break to maturity shortened systematically when the climate became warmer. Maturity in the hotter sites (CopiapoValley) was 1 to 2 months earlier than in the cooler sites (AconcaguaValley) (Table 2). In the earlier phases of the life cycle, differences among cultivars are rather small. As it moves forward in the cycle, differences star to express clearly, and degree-days required for accomplishing latter phenological phases, increase more in later cultivars than in the earlier. The main differences among cultivars are observed after fruit maturity. Mathematical models for each cultivar are summarized in table 3. The Mitcherlich model fitted well with experimental data in the three cultivars as shown by figures 1, 2 and3. The determination coeficients are shown in table 3. In the three varieties the model slightly under estimates the development rate during fruit development, between fruit set and véraison. However, considering the whole period from budburst to harvest, the model fit well with experimental data [stages 3 to 38], having a good predictive capacity of harvest-ripe stage. This could be due to an excesive number of phenological stages considered, in this section of the life cycle, by the Eichhorn & Lorenz scale. After harvest-ripe stage, development is also well represented until initial leaf senescence [stage 43]. It seems that the evolution of senescence after the 43rd stage is controlled more by low temperature than by degree-days. Cultivars like Perlette, which are harvested early and whose leaves senescence occurs during the warm season, show a smooth progression of the last phenological phases. In contrast, late cultivars like Red Globe, the senescence of leaves occurs later in the fall, being accelerated by low temperatures, shortening the last phenological phases until reaching leaf drop (Figure 4). As shown by figure 4, cultivars have different development rates in terms of development units, ELu/D_{days} [slope of the Mitcherlich curve] depending on precocity. This phenomenon is clearly expressed after the first leaf has emerged. During flowering and fruit development (stages between 7 and 35), early varieties show a marked acceleration on this development rate with respect of late varieties. This suggest that precocity is more related with the reproductive phase than with the whole life cycle, being probably and adaptation strategy of plants to populate most hostile climate. These differences accumulated during the phenological cycle, have an impact on the precocity of different cultivars, which seems to have a strong genetic control. This fact leads different cultivars to have different degree-days requirements, and to convert degree-days into development units.

Table 2. Observed Harvest date in three valleys of Chile

Cultivar	Harvestmaturity date					
	Copiapovalley		Huascovalley		Aconcagua valley	
	Early	Late	Early	Late	Early	Late
Thompson Seedless	1-Dec	28-Jan	25-Dec	10-Jan	2-Feb	4-Mar
Redglobe	6-Dec	14-Feb	6-Jan	29-Jan	19-Feb	6-Apr
Perlette	13-Nov	21-Nov				

Table 3. Mitscherlich monomolecular models representing phenological progression

Cultivar	$Ph_{stage} = Ph_{final} \bullet (1 + Ph_{ini} \bullet \exp(- K_{shape} \bullet D_{days}))$	r^2
Thompson Seedless	$Ph_{stage} = 40 \bullet (1-\exp(-0.0028 \bullet D_{days}))$^3	0,97
Redglobe	$Ph_{stage} = 39 \bullet (1-\exp(-0.0028 \bullet D_{days}))$^3.5	0,99
Perlette	$Ph_{stage} = 42 \bullet (1-\exp(-0.0035 \bullet D_{days}))$^4.6	0,98

D_{days} = Degree Days base 10 (ºD$_{10}$).

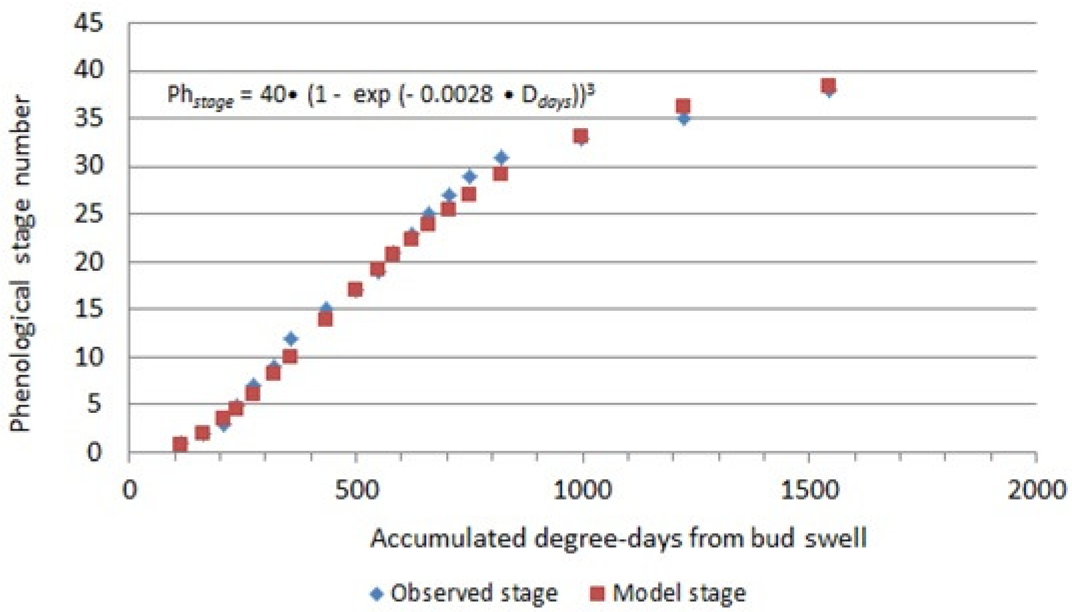

Figure 1. Thompson Seedless phenological model

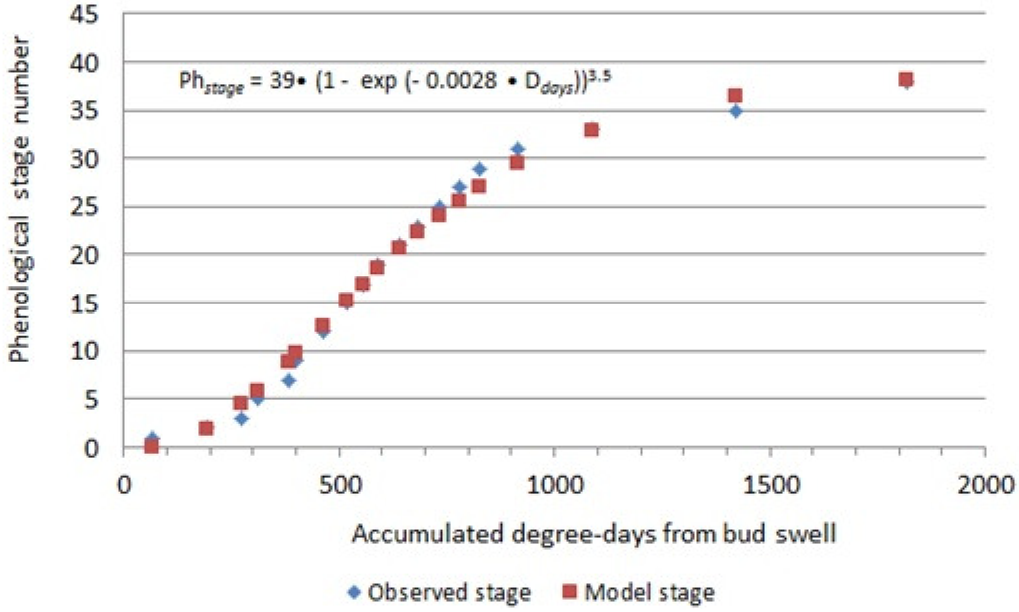

Figure 2. Redglobe phenological model

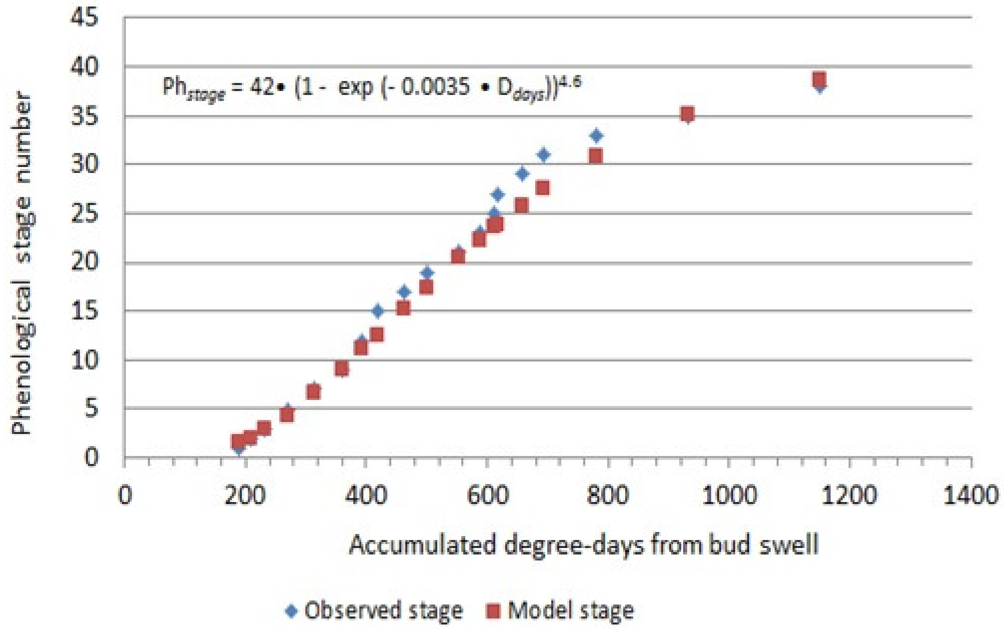

Figure 3. Perlette phenological model

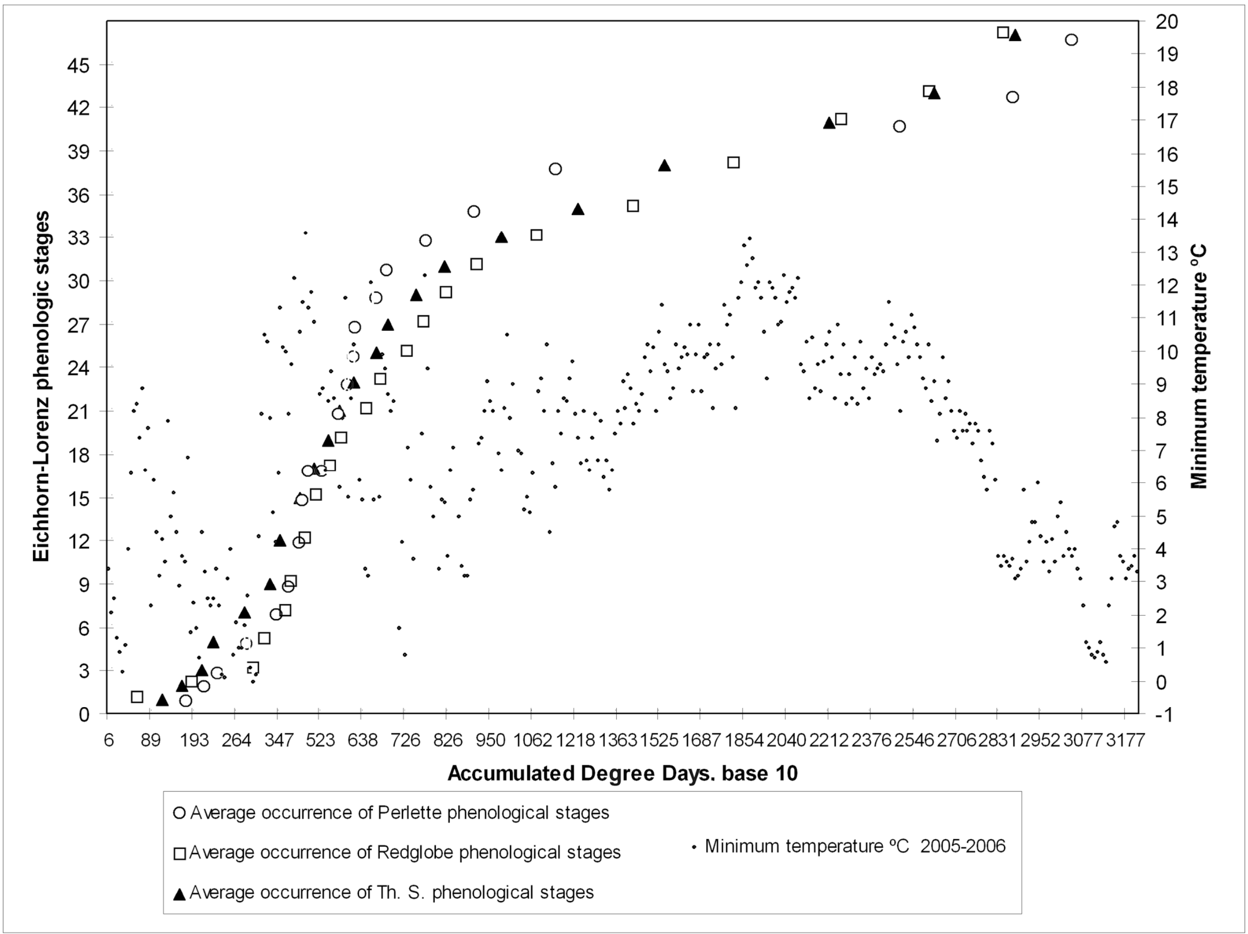

Figure 4. Minimum temperatures and phenology of table grape cv. Thompson Seedless, Red Globe and Perlette in Copiapo valley, seasons 2005-2006.

Considering that development rate depends also on several climatic factors like winter dormancy, mean temperature at bud burst (Moncur et al.1989; Lombard et al.1979) and solar radiation (Failla et al. 2004), high temperature (Sadras and Moran, 2013), it is difficult to find a universal model to predict vine phenology. For this reason, degree-days requirements for a specific phenological phase and for the same cultivar, may vary from one site to another. For example, Williams et al. (1985) observed Thompson seedless bloom between degree-days 400 and 500, while our observations show the same phenological event in Chile occurring between degree-days 500 and 650. This variation would be associated with the effect of other climatic drivers (high stressing temperatures, solar radiation, atmospheric water demand which regulates midday stomatal closure and then diurnal leaf temperature.

Degree-days requirements for maturation vary from 1150 D_{days} in Perlette (early cultivar) to 2050 in Crimson Seedless (late cultivar). Once reaching maturation, each cultivar needs a specific lapse to accumulate reserves of carbohydrates after harvest and before leaf drop.

After fruit ripeness, the length of leave life seems to be strongly controlled by low temperatures which interact with the photosynthetic system (Hoch et al., 1999; Fryer et al., 1998). For this reason, the length of the period going from harvest-ripe to leaf senescence is a key factor in the adaptation to climate of a specific cultivar. Considering the fact that low temperatures, below the minimum growing threshold of 7℃ (Mariani et al, 2012), trigger leaf senescence, the best climate for an specific cultivar is that which guarantees a post-harvest period of at least one or two months with temperature above this threshold, in order to give the possibility of accumulating enough carbohydrate reserves. Thus, climates with milder winters are good for late season cultivars (Crimson Seedless, Autom Royal, Princess, Red Globe, Thompson Seedless), while climates with colder winters are more suitable for early season cultivars (Perlette, Flame Seedless and Sugraone). The length of this postharvest period suitable for carbohydrate production and accumulation is considered an index of the level of adaptation of each cultivar to a specific climate.

Early season cultivars, such as Perlette, Flame Seedless and Sugraone, have lesser degree-days requirements to complete fruit maturity from full blossom (embryogenic phase, 600 to 650 D_{days}) than late season cultivars such as Redglobe, Crimsom Seedless (1100 to 1500 D_{days}). Inversely, the more degree days required for embriogenic phase, the fewer the available degree days for the carbohydrates accumulation period (Figure5). This makes the late season cultivars more sensitive to early season frosts, than early season cultivars.

From bud burst to full blossom, degree-days requirements in early phenological phases vary slightly (about 650 $D_{days} \pm 50$). Differences among cultivars start to increase in the time from full blossom to leaf drop. Phenological progression seems to be a gradual sequence of phenotypic transformations whose climatic determinism allows their representation with mathematical models. These models may help in creating predictive capacities, assessing climatic potentialities and understanding the behavior of the vine in different productive contexts.

Model Test

The four selected phenologic stages had a similar behavior and climatic determinism. The total accumulated degree-days to accomplish a specific stage seem to slightly vary, depending on solar radiation and cold or hot waves which interrupt the normal accumulation of degree-days. To include these effects, a more complex model should be built, considering an efficiency factor of the thermal units. Despite these sources of error, in the case of vine, models based on the simple accumulation of degree-days, seems to have a high predicting capacity of phenological stages. Considering the results reported in table 4, the mean error of the model estimations, for all phenological stages, was 23, 32 and 27 degree-days in the three campains (years 2010, 2011, 2012). At a mean temperature of 10°C, this meansan error of 2to 3 days in the estimation of dates of occurrence of the four phenological stages (Figure 6).

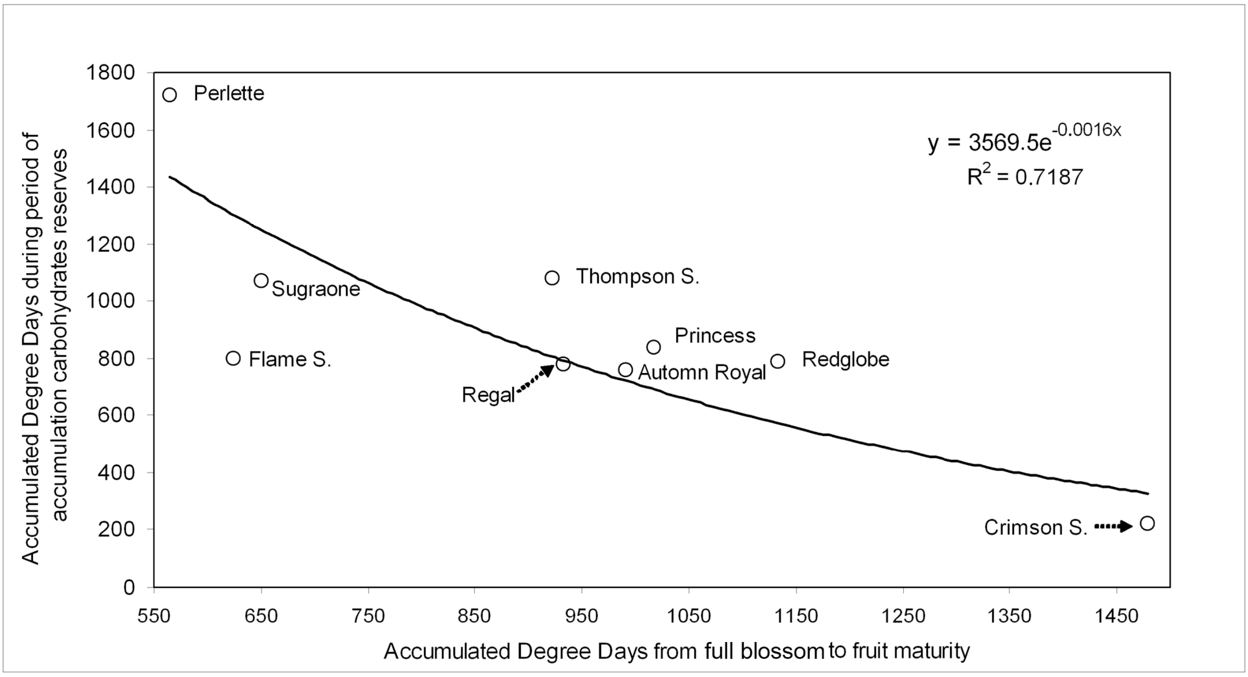

Figure 5. Accumulated degree days in the post harvest period *versus* accumulated degree days in the embryogenic (full blossom to maturity) period for nine cultivars. (Early cultivars: Perlette, Flame and Sugraone; Late cultivars: Red Globe and Crimson S.).

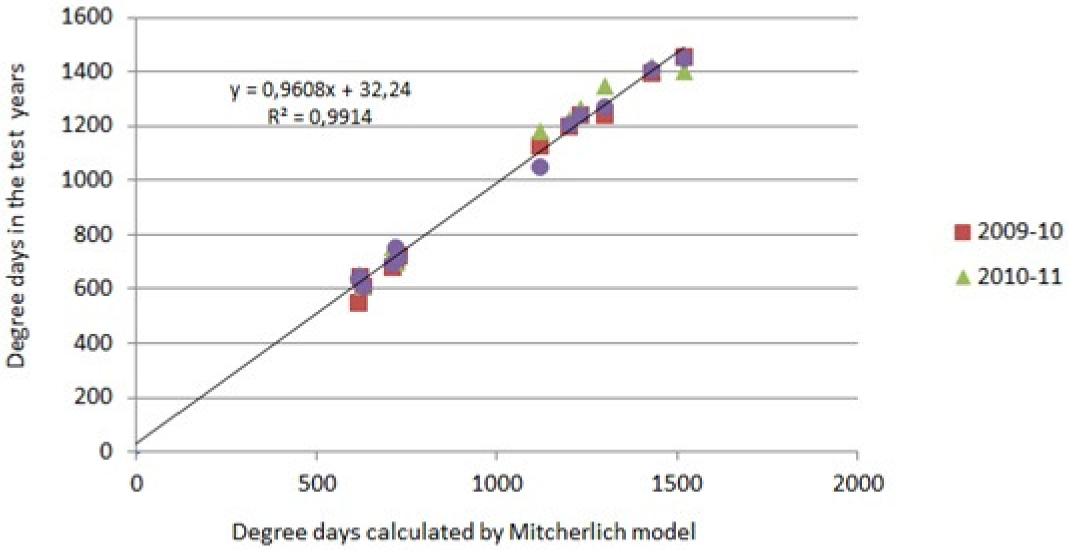

Figure 6. Model test. Degree-day corresponding to observed phenological stages along three years and calculated degree-days for each stage. Three varieties (Thomson seedless, Redglobe and Perlette) and four stages (full blossom, fruit set, veraison, harvest ripe)

Conclusions

Vine phenology has a strong climatic determinism. Experimental evidence shows that the concept of degree-days, while simple, is a good bioclimatic predictor of the phenologic sequence of plant species.

Development rate tend to descelerate as it moves in the cycle. The Mitscherlich monomolecular equation seems to be very useful to model this kind of dynamics using accumulated degree-days as the control variable.

In the early phenological cycle, cultivars do not show many differences in its developmente rate. Differences clearly arise after flowering. As a consequence of the difference in precocity, the number of degree-days accumulated between fruit maturity and leaf drop is higher with early cultivars than with late cultivars, which is an advantage of early varieties to adap to climates with early frosts in the fall.

Considering the regularity in the rate of development, which fit well with a monomolecular model, it is unnecessary to use 47 stages to describe phenological progression. Instead, this progression may be reduced to the main phenological events. For practical purposes we recommend the observation of: bud burst, flowering, fruit set, veraison, harvest and start of leaf drop.

Modeling phenology of fruit species on a bioclimatic basis holds significant potential in providing a predictive tool for biological events, which can contribute to optimizing the management of productive orchards.

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