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Performande of a Chill Overlap Model for Predicting Bud Break Prediction In Chardonnay Grapevines Over A Broad Range of Growing Conditions

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Abstract: Predicting phenological stages through modelling has significant applications for planning viticultural practices as well as for predicting climate change impacts on phenology. The Chill Overlap Model is based on an exponential declining curve to integrate the demonstrated compensatory relationship between chill and heat accumulation, and it incorporates recent research-based knowledge of physiological changes during dormancy. The aim of this work was to develop parameters for a Chill Overlap Model for predicting bud break in Vitis vinifera cv. Chardonnay grapevines and determine if using a Chill Overlap Model could be used to predict bud break better than previously developed models. The Chill Overlap Model that was developed also
incorporated the use of the Dynamic chill accumulation model for quantifying accumulation of chill exposure with a cultivar that has a relatively low chill requirement. Bud break data from Californian and Spanish wine grape regions representing a wide range of climates were used to parameterize a Chill Overlap Model for Chardonnay. The newly developed Chardonnay Chill Overlap Model did not succeed in predicting bud break better than previous efforts, but it did point out significant differences between the dynamics of chilling in grapevine compared to other species on which the Chill Overlap Model was developed. Further research is needed to account for environmental and vineyard management factors that influence bud break timing in order to further improve the model and better understand factors that influence completion of dormancy in grapevines.

**Keywords:** chill and heat requirements, chill portions, Dynamic chill accumulation model, modelling, phenology, temperature

**Introduction**

Phenological models have relevant applications in viticulture, from planning viticultural practices (Williams et al. 1985, Caffarra and Eccel 2010) to modelling carbon dioxide fluxes (Richardson et al. 2013, Pope et al. 2014). Recent research has focused on predicting climate change impacts on plant phenology to develop strategies to mitigate its possible effects on crop behavior (Chuine 2000, Richardson et al. 2013, Darbyshire et al. 2016).

Bud break in grape indicates the onset of vegetative growth (Duchêne et al. 2010). Any delay during this stage can have impacts on the seasonal growth cycle, making it a key phenological stage with large site and cultivar variability (García de Cortázaro-Atauri et al. 2009). Ambient temperature is widely considered to be the main
climatic driver responsible for phenological development (Williams et al. 1985, Martin and Dunn 2000, Jones 2003, Garcia de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010, Duchène et al. 2010, Nendel 2010). But other factors have been reported to modify grapevine phenology, such as soil temperature, soil texture (Jones 2003), photoperiod and water stress (Parker et al. 2013).

Dormancy is described as a temporary suspension of growth caused by physiological changes in buds (Lang et al. 1987). The timing of dormancy release depends on the exposure of buds to winter chill for ending endodormancy, followed by a period of spring heat to release ecodormancy and finally trigger bud break (Caffarra and Eccel 2010, Pope et al. 2014). Chill and heat are needed to release correspondent dormancy stages, resulting in specific temperature exposure requirements for different species and cultivars (Chuine 2000).

Grapevine growth models that predict bud break are mainly based on the computation of heat accumulation during spring, also known as Thermal Time (Cannell and Smith, 1983), from a set date until reaching a species-dependent threshold. These models are referred to as Spring Warming models (Hunter and Lechowicz, 1992). Under these models chilling requirements are assumed to be met every year (Pope et al. 2014), but these types of models may be inappropriate for Mediterranean climates, with occasional mild winters when minimum amounts of chill are not met (Pope et al. 2014) or for areas where climates are trending toward warmer winters (Luedeling and Brown, 2011). Other models, called sequential models, are structured with winter chill and spring heat accumulation being treated as independent phases fulfilled sequentially (Kramer 1994).

Complex sequential models, developed for Chardonnay and other cultivars, further integrate knowledge about developmental responses to environmental drivers.
Adding more biological and physiological explanations about grapevine crops into a phenological modelling framework, García de Cortázar-Atauri et al. (2009) developed the BRIN model. This was the first grapevine model to predict bud break based on physiological mechanisms as a framework for the heat accumulation approach. Caffarra and Eccel (2010) built the FENOVITIS model for the Chardonnay (Vitis vinifera) cultivar by adding complex model parameters to integrate a negative relationship between the chill and heat accumulation stages with set chilling requirements previously described by Cannell and Smith (1983), Chuine (2000) and Harrington et al. (2010).

It is often assumed in deciduous tree studies that chilling and heat accumulation requirements have to be fulfilled one after the other up to a fixed threshold, but this sequential fulfilment of chill and heat requirements is based on a simplified understanding of dormancy breaking processes (Luedeling et al. 2009). The measurement of the specific periods when buds are influenced by chilling and warming temperatures is challenging (Chuine 2000). Moreover, complex processes are likely to be involved in the transition from dormancy to bud break in grapevine (Fila et al. 2014). It is known that specific proteins appear to contribute to the induction and release of bud dormancy, but extensive molecular biological analyses are required to further understand the physiological, biochemical and genetic basis of grapevine bud dormancy (Lavee and May 1997, Nendel 2010).

Major changes in dormant buds occur when chilling requirements are fulfilled, such as changes in membranes or in the fatty acid ratios in phospholipids (Faust et al. 1997). Research has shown that the relationship between chilling, post-rest and bud break is complex. According to recent knowledge on genetic dormancy control (Horvath 2009, Leida et al. 2012) Pope et al. (2014) suggested that there could be a large overlap between chill and heat requirements because, after the minimum chill
requirement is met but before bloom in peach (*Prunus persica*), there was decreased expression of the genes responsible for response to cold with continued chill exposure (Yamane et al. 2011).

Following these principles, recently developed Chill Overlap Models attempt to integrate possible interactions between chill and heat accumulation by fitting an exponentially declining curve to describe decreasing requirements for post-chill heat accumulation in response to higher exposure to chilling temperatures, contemplating a partial compensatory relationship between chilling and post-chill heat requirements to finally trigger bud break (Pope et al. 2014). The conceptual basis for the model, compared with other recently developed models for Chardonnay, might help to increase understanding of the biological and physiological behavior of grapevines during the dormancy period. Chill Overlap Models have been developed for almond (*Prunus dulcis*) and apple (*Malus domestica*) deciduous trees, achieving a prominent improvement over previous model predictions (Pope et al. 2014, Darbyshire et al. 2016).

Furthermore, with the Chill Overlap Model, chill accumulation is calculated with the Dynamic chill accumulation model (Fishman et al. 1987), which has been found to perform either better, or equivalent, to other commonly used chill accumulation methods for various locations and cultivars (Erez 2000, Ruiz et al. 2007, Luedeling et al. 2009, Pope et al. 2014, Darbyshire et al. 2016). The negation of chill due to high temperatures that is imbedded in the Dynamic chill accumulation model has not been tested for grapevines but it could provide interesting perspectives for bud break predictions in warm climates (Dokoozlian 1999, Fila et al. 2014).

The aim of this work was to develop parameters for a Chill Overlap Model for predicting bud break of the Chardonnay grape cultivar and determine if such a model
would improve bud break prediction over a broad range of growing conditions. Bud break data across Californian and Spanish growing regions were used to develop and test model predictive capacity from observations over a range of diverse locations for evaluating the reliability of the model in different climates.

Materials and Methods

Bud break and weather station data

Bud break data of the Chardonnay cultivar were used to parameterize and validate the performance of the Chill Overlap Model (Pope et al. 2014). Wineries and research institutions across Californian (USA) and Spanish regions provided phenological data from different locations (Figure 1). Bud break was considered to be achieved when 50 % of buds were open, but a specific scale was not used in all data sources.

Daily maximum and minimum temperature data were acquired from the nearest weather station to each vineyard site (Table 1). Weather data for California (USA) were obtained from the California Irrigation and Management Information System (CIMIS, www.cimis.water.ca.gov). In Spain, weather data were retrieved from the Meteorological Service of the Catalonian Government (SMC, www.ruralcat.net/web/guest/agrometeo.estacions) (Raïmat and Sant Sadurni d’Anoia locations) and the Irrigation advice network of Extremadura (REDAREX, redarexplus.gobex.es/RedarexPlus/) (Badajoz location) (Figure 1). For occasional instances of periods of missing temperature data at a specific station, data from the nearest weather station were used as substitute data. In a few instances when several phenology observation sites were located near the same weather station (i.e. Windsor, Carneros), mean bud break data was calculated and used with temperature data from that station.
Phenology data were divided into two independent parameterization ($n=42$) and validation ($n=39$) subsets to cover the most representative climatic conditions, and to test the robustness of the model (Figure 2).

**Chill Overlap Model description**

The Chill Overlap Model is based on an exponentially declining curve to represent the possible combinations of chill accumulation ($C_a$), and heat accumulation ($H_a$) that result in bud break (Harrington et al. 2010). Two sub-models were used to quantify winter chill and spring heat from the onset of the dormancy period until bud break (Pope et al. 2014).

Chill was determined with the Dynamic chill accumulation model (Fishman et al. 1987), and involved a two-step process. In the first step, a chill intermediate was formed or destroyed according to an hourly bell-shaped temperature relationship. There was an enhancement of formation of chill intermediates in cold temperatures with an optimal efficacy at 6-8 ºC, and the negation of previously accumulated chill intermediates if there were temperatures above a specific threshold (24ºC). In a second step, the chill intermediate was computed as one Chill Portion (CP), equivalent to 30 hours at continuous chill exposure at 6ºC (Erez and Fishman 1998), where later warmer temperatures could not negate it. Heat was calculated using the Growing Degree Hour (GDH) ASYMCUR Model (Anderson et al. 1986). The acquisition of heat was an hourly asymmetric curvilinear model defined by two cosine equations with three threshold temperatures (base temperature=4ºC, optimum temperature=25ºC, critical temperature=36ºC), which determined the accumulation of Heat Units (HU). A base temperature of 10ºC it was also tested with this model.

Hourly temperatures were required as inputs to the Dynamic chill accumulation model and GDH ASYMCUR Model. Following Linvill (1990) equations, daily...
maximum and minimum temperatures were interpolated into hourly data, with the specific parameters of each weather station location, for both the parameterization and validation datasets (Table 1).

The chilling requirement \( C_r \) is the minimum amount of accumulated chill needed for bud break to be possible, and the heat requirement \( H_r \) was the minimum accumulated heat required for bud break to be possible. According to Pope et al. (2014), \( C_r \) should be met before additional chill \( C_a \) modifies a specific part of the heat accumulation \( H_o \) phase resulting in an overlap between both phases, defined by Eq. (1) and (Figure 3):

\[
H_o = \beta_1 + \frac{\beta_2}{e^{(\beta_2 \times C_a)}} \tag{1}
\]

- \( H_o \), heat accumulation from \( C_r \) to bud break
- \( C_a \), chill accumulation after \( C_r \) is met
- \( \beta_1, \beta_2 \) and \( \beta_3 \), model parameters

The \( \beta_1 \) model parameter, defined the lowest heat accumulation when bud break was possible, being equivalent to \( H_r \). In fitted models it correlated with heat accumulations experienced in high chill years/climates. \( \beta_2 \) corresponded to the difference of heat accumulation between the highest and the lowest observation values \( (\beta_2 = H_o - H_r) \), estimated by data accumulated during mild winters. \( \beta_3 \) parameter was related with the shape of the curve with values ranging between 0 and 1 defining that shape (Pope et al. 2014).

**Model parameters development and parameterization**

The Chill Overlap Model parameters were fitted following Pope et al. (2014) and Darbyshire et al. (2016). The chilling requirement \( C_r \) was estimated, since there were no previous experiments conducted to evaluate it. The onset of chilling was considered to occur on October 1 (Jarvis-Shean et al. 2015). The minimum value of
chill accumulation measured through the period across all sites and years (October 1 to March 31) was tested as the maximum \( C_r \) with 1 CP increments and a range of 1 to 31 CP (Spain - Sant Sadurni d’Anoia, 2012). The tested overlap interval values were from 10 % to 90 % with increments of 5% (Figure 3).

For each \( C_r \) tested, starting values to fit model parameters were estimated from parameterization datasets. The lowest value of \( H_o \) was used as an estimation of \( \beta_1 \), the difference between the highest and the lowest \( H_o \) values was estimated as \( \beta_2 = H_o - H_r \), and the starting value for \( \beta_3 \) was 0.0001 (Eq. 1).

Non-linear regression algorithms were applied to fit the model. The Levenberg-Marquart algorithm in the Curve Fitting Toolbox of MATLAB software (MATLAB and Statistics Toolbox Release 2014b, The MathWorks, Inc., Natick, Massachusetts, United States) was chosen instead of a trust-region algorithm, because it required fewer iterations to find properly fit values for the model. Negative values of \( \beta_1 \) and \( \beta_2 \) where dismissed for lack of biological sense, i.e. heat accumulation cannot have negative values (Pope et al. 2014).

**Model parameter evaluation**

To obtain model parameter values, three indices were evaluated. The information-theoretic approach Akaike Information Criterion (AIC\( _C \)) was evaluated comparing within each \( C_r \), the model with the lowest value of AIC\( _C \) (Burham and Anderson, 2002). Models with different \( C_r \) could not be compared because of the change of the response variable that resulted in lower \( C_r \) to earlier heat accumulation (Pope et al. 2014). Candidate model parameters were also evaluated considering \( R^2 \) and Root Mean Square Error (RMSE) values. Models with better model parameters were evaluated in the same way using the validation dataset.
Results

Selected candidate models prioritized according to the lowest AICₐ, high R² and low RMSE values using parameterization data are shown in Tables 2 and 3. Testing several overlaps (from 10 to 90% with increments of 5%) for the range of Chill Portions selected (from 1 to 31), the AICₐ with a value of 346.62, a R² of 0.54 and a RMSE of 8.86 were achieved with a Cr of 9 CP and a 40% overlap (Table 2) (Figure 4A, Figure 4B). The corresponding Chill Overlap Model parameter values were 6110, 9657 and 0.0463, for β₁, β₂ and β₃, respectively (Figure 4A). The evaluation of the same overlap with different chilling requirements is shown in Table 3. Changing the Cr value from 9 CP did not improve the performance of the model.

Validation of these parameters was conducted by applying the same model parameters to an independent dataset. The model fit for the validation data set was better than for the parameterization data set and, a Cr of 9 CP, and a chill-heat overlap of 40%, resulted in an R² = 0.69, and a RMSE of 7.32 days (Table 2 and Table 3) (Figure 5), thus indicating that the previously chosen model parameters were as valid as could be expected.

Model RMSE analysis was more accurate for data from the Central Valley (CA), with 7.09 and 6.13 days, for parameterization and validation, respectively. Model performance was less accurate in warmer winter locations such as the Central Coast (CA) (9.00 for parameterization and 10.00 days for validation) and South Central Coast (CA) (10.60 for parameterization and 8.49 days for validation) (Table 1). This may have been because fewer data points from these locations were available for initially fitting the model. (Figure 4B, Figure 5).
Discussion

Model approach

In accord with the structure of the Chill Overlap Model, in addition to $C_r$, colder locations accumulated more chill and decreased the heat needed to reach bud break, whereas warmer locations accumulated less chill, and more heat was required to trigger bud break. In our study, observations in cooler conditions presented later bud break (Spain), and warmer conditions presented earlier bud break (Central Coast and South Central Coast California locations) (Table 1). A delaying effect due to high temperatures during dormancy induction has been reported for Chardonnay, indicating mild temperatures might contribute to earlier dormancy during fall, whereas warm temperatures above 20ºC delay it (Caffarra and Eccel 2010). But with Chardonnay low temperatures during the same period led to a more rapid chill accumulation, and earlier ecdormancy transition (Cragin et al. 2017).

The parameterizing dataset seemed to provide sufficient data with extreme values to approach $C_r$, $H_o$ and $H_r$ to consequently fit model parameters. The estimated parameters presented some differences between the starting values and the fitted parameters (data not shown). The lower the $\beta_3$ fitted value was, the more linear was the relation between $C_a$ and $H_a$, and thus, the lower the value of $\beta_1$ and the higher the value of $\beta_2$, but not in all the cases that were analyzed (Table 2, Table 3). These discrepancies were difficult to explain by the curved relationship between chill and heat, given numerous studies showing this relationship in temperate perennial species (Chuine 2000, Harrington et al. 2010). To gain further insights into an appropriate model, experimental determination of $C_r$ could be used to fit the value directly rather than trying various $C_r$ options and increasing model curvature to compensate for this lack of knowledge (Dennis 2003, Pope et al. 2014). To provide further insight into the accuracy
of fruit trees models, the addition of endodormancy break dates are needed to yield more robust projections of phenological changes (Chuine et al., 2016).

Model performance

The Chill Overlap Model developed in this research did not substantially improve bud break accuracy prediction considering previously developed phenological models for the Chardonnay cultivar, under specific locations and climatic conditions (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010), or comparing the accuracy improvement for the predictions in other species that have been tested (Pope et al. 2014 and Darbyshire et al. 2016). In this study the data used in model development covered a wider geographical area for the Chardonnay cultivar than in previous studies and this may have been one reason for the modest accuracy.

Varied phenological data sources may also have been an important reason for the limited accuracy of the developed model, because criteria for determining the exact onset of bud break was not uniform across sites and locations. Although bud break was generally considered when 50% of buds were open, determination of the exact day of bud break likely varied depending on the days between observations and the person who was taking the data. Also, weather data was not recorded directly adjacent to the vines whose phenology was observed. There may have been differences between temperatures recorded at the weather stations and temperatures experienced in the vineyards, particularly due to differences in altitude (Nendel 2010) or aspect.

Furthermore, maximum and minimum daily temperature data were used to estimate hourly chill and heat accumulation. The use of actual mean hourly temperature would have been more accurate for determining temperature accumulation but these data were not available for all sites.
Clonal behavior also likely varied in different locations, presumably affected by microclimates and soils, leading to diverse clonal performance under different conditions (Jones et al. 2014). In addition, it has been reported that yield and yield components differ among clones of Chardonnay depending on yearly clonal interactions (Fidelibus et al. 2006). It may be that there was some error in bud break prediction in this study due to unaccounted for clonal variability in the Chardonnay cultivar.

Variability of phenology in the same location may be explained by microclimate (Verdugo et al. 2016). Microclimate could affect phenological development as a consequence of particular changes in environmental conditions. California region phenology performance might have been affected by this phenomenon in the Central Valley and especially in the North Coast regions (Figure 4B, Figure 5). Another important factor may have been the distance between the weather stations and the observation vineyards (Table 1). Even though the Central Valley (CA) region is characterized as being flat, the distance between site and weather stations could be more than 10 km, and this could have been a source of error in model performance.

Air temperature has been widely described to be the main phenological driver. Depending on the net radiation, differences between air and bud temperature tend to be 0.5 – 2°C, but on foggy days the relationship changes to −0.1 – 0.2 °C (Itier et al. 1987).

Fog tends to decrease bud temperature and thus increases chill accumulation, but fog formation is highly variable on a year-to-year basis because of many complex and conditional meteorological factors. The general trend in the California region has been a decrease of winter fog events that are characterized by sustained periods of air temperatures below 7°C. Possible consequences of less fog are warmer air and an increment in the energy balance of buds, which amplifies their warming, and reduces their chill accumulation (Baldocchi and Waller 2014).
Orchard management might also have potential for influencing microclimate through small effects caused by planting density, pruning practices, cover cropping and irrigation regime (Luedeling et al. 2009). Grapevine management practices have been reported to influence bud break completion. In postharvest irrigation experiments, early cut off of irrigation have been reported to advance bud break stage with the Perlette cultivar (Williams et al. 1991). Similar responses were observed in an experimental vineyard of Chardonnay in Raïmat, Lleida, Spain, during spring 2016 (J. Marsal personal communication). Late pruning slightly delayed bud break with Cabernet Sauvignon (Martin and Dunn 2000) and Sauvignon Blanc grapevines (Trought et al. 2011).

**Chill and heat accumulation**

According to Faust et al. (1997) and Chuine (2000), specific changes in dormant buds do not occur until a minimum amount of chilling units are accumulated, and bud growth does not respond to warm temperatures during endodormancy. Over a range of temperatures chill accumulation in grapes was evaluated to be most efficient at 2.8 °C (Caffarra and Eccel 2010). A recent study conducted with Chardonnay canes indicated that -3 °C was also an effective temperature for endodormancy release after three weeks of cold exposure (Cragin et al., 2017). The Dynamic chill model, used to evaluate chill accumulation in the Chill Overlap Model, considered 6-8°C to be the optimum temperature range for chill accumulation. Furthermore, this model considers the effect of negation of chill due to a period of temperatures above 20°C. To our knowledge the Dynamic Chill Model has not been previously tested for grapevines species (Dokoozlian 1999). Even though chill models described in the literature are often not comparable because the amount of chilling units differ among sites, previously tested chill models and the experiments performed in grapevines provide some basis for
Dynamic chill accumulation model seemed to be appropriate for measuring chill in this study because of the range of climates present in the dataset.

For most plants, 10 °C is generally considered as the base temperature below growth does not occur. According with Williams et al. (1985), 10 °C was the base temperature for heat accumulation in grapevines, but several references show that it might be different for bud break prediction. In a study of phenological predictions Duchêne (2010) argued that a base temperature of 10°C might not be the most appropriate for bud break. Experimental studies found temperatures around 5°C to be the more appropriate for bud break predictions (Moncur et al. 1989) and García de Cortázara-Atauri et al. (2009) found better performance using 5°C as a base temperature for Chardonnay.

In this study, the Growing Degree Hour (GDH) ASYMCUR Model (Anderson et al. 1986) was used for heat accumulation determination considering a base temperature of 4°C. A base temperature of 10°C during the endodormancy release period was also tested, but no improvements in model predictions were achieved. Thus, it seems that a base temperature below 10°C may be suitable for bud break prediction, as it has been used in previously developed models for the Chardonnay cultivar (García de Cortázara-Atauri et al. 2009).

The point of this research was not the determination of the threshold temperature values for chill and heat accumulation, thus the most common or apparently most suitable temperature values available from the literature at the time of the study were used. Further research is clearly needed on the evaluation temperatures for the perception of chill and heat by buds during dormancy, but because of other limitations
on the dataset used in this study it was not appropriate to pursue this objective in this study.

Other factors like a lack of synchrony in bud growth, where apical buds open before than lateral buds because they meet heat requirements earlier (Martin et al. 2000), differences in bud vigor, and amounts of carbon and nitrogen in reserves might also affect the perception of chill and heat temperatures by buds (Ben Mohamed et al. 2010).

In this study Chardonnay was found to need ~9 CP compared with 13, 21 and 23 CP for the Sonora, Mission, Nonpareil almond cultivars, respectively (Pope et al. 2014), and 34 CP for the Crisp Pink apple cultivar (Darbyshire et al. 2016). Compared with other deciduous fruit crops, Eshghi et al. (2010) reported that grapevines in Iran do not have high chilling requirements and need relatively little exposure to chill. Our results are consistent with this report. Considering that 1 CP is equivalent to 30 hours at continuous chill at 6°C (Erez and Fishman 1998), the evaluated chilling requirement for Chardonnay might be similar to a chill exposure of 270 hours (9 CP x 30 hours/CP). Previous research using chill hours accumulated between 0 and 10 °C found that 200 hours was the minimum chilling exposure required for normal bud grape growth for the Perlette cultivar (Dokoozlian, 1999), and 336 hours at temperatures below 6°C for Cabernet Sauvignon (Botelho et al. 2007). Chill hour requirements for Nonpareil almond have been reported to be 360 hours (Ramírez et al. 2010), while the requirements for Gala and Sweetheart apples have been reported to be 973 and 687 chill hours under 7.2 °C, respectively (Guak and Neilsen, 2013).

Although there is no exact equivalency between Chill Hour and Chill Portion quantification because they are not constant in time or space, it is reassuring that the differences in chill requirements ($C_r$) between species are consistent with different chill
models, accentuating biological species differences. Some studies have suggested that
the Dynamic chill accumulation model is more accurate for quantifying winter chill,
reducing location and year-to-year variability and performing better in warmer areas
(Luedeling et al. 2009).

Differences among species can be highlighted by comparing values of the Chill
Overlap Model parameters. Emphasizing the low chill necessity in grapevines, the
overlap defined by the period with a compensatory relationship between chill and heat
requirements appeared to be lower in grapevines (40 %) than almonds and apples (75
%) (Pope et al. 2014 and Darbyshire et al. 2016). As hypothesized by Pope et al. (2014),
the amount of overlap might vary by species. Grapevines appear to be less demanding
of chill even in the compensatory stage between both requirements. On the other hand,
along with a low chill demand, Chardonnay appeared to need the perception of more
heat, as shown in the $\beta_1$ fitted model parameter. This suggests that grapevines may be a
species in which additional heat may be more effective than additional chill above the
minimum chill requirement ($C_r$).

Based on the Chill Overlap Model, the contribution of chill and heat to bud
break differs between grapevines and apples. Once $C_r$ is met in both species, cool
locations with considerable accumulation of chill and subsequent decrease of heat
demand presented later bud break observations in grapevines, but earlier bloom in
apples. In warmer locations more heat was required to meet bud break conditions and
grapevines had earlier bud break, while with apples it took additional time for
flowering, delaying this stage (Darbyshire et al. 2016).

Values of $\beta_3$ defined similar curves of roughly the same shape, but with different
chill and heat requirements among species. Additionally, a more precise estimation of
chilling requirements by forcing or growth-room experiments could increase model
A previous study demonstrated that models calibrated with growth room data provided good accuracy when tested on two different field-based datasets (Fila et al. 2012). The integration of data obtained by growth room experiments combined with field observation data may yield more accurate model estimates (Fila et al. 2014). Other aspects like the addition of the time of pruning into the models might also improve model performance (Martin and Dunn 2000).

More research to improve phenology models for making accurate predictions is necessary considering the potentials impact of climate change on the suitability of specific grape cultivars for specific future growing regions. The results of the Chill Overlap Model for Chardonnay grapevine did not significantly improve bud break predictions over previous more simple models (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010). But the fact that the model attempted to integrate the overlapping effect of chill accumulation on the subsequent heat accumulation requirements, that have been empirically observed in the field, indicates that it would be worthwhile to try to improve the model by accounting for several of the sources of potential non-temperature related variability in bud break pointed out in this work.

Conclusion

This study provided a new set of parameters for modelling bud break in Chardonnay grapevines using the Chill Overlap Model. Even though model performance did not show substantial predictive improvements over previous bud break models, the model obtained can be considered as an approach for taking into consideration the synergistic interactions between chill and heat accumulation requirements prior to bud break in grapevines. The results were acceptable considering the wide range of climates involved and potential sources of inaccuracy in the data sets.
used. Knowledge of the possible influences of environmental factors and management
practices in specific locations, should help in reducing inaccuracies of the predictions
obtained, and lead to further model improvement.

The study confirmed the apparent low chill requirement of Chardonnay, and that
temperatures below 10°C seemed to be effective in fulfilling the chill requirement. On
the other hand, Chardonnay is known to be a cultivar that needs substantial amounts of
warm temperatures to achieve bud break, and this should be carefully considered in
order to understand how the rise of temperatures due to climate change could affect its
behavior and adaptability.

This model includes potential interactions between cold and warm temperatures
that could help to further understand the physiology and crop behavior during dormancy
and bud break. Even though all phenological models present simple interpretations to
predict complex realities, the basis of this model presents enough complexity and does
not need expensive experiments for evaluating its performance.

Fitted model parameters differ greatly among species and emphasize the
relevance of phenological data collection for individual species and cultivars, and the
importance of sharing information over different climatic conditions and locations, to
provide more reliability and improvement of phenological model performance. The low
percent overlap in chill and heat accumulation with Chardonnay, compared to the high
overlap in the models for almond (Pope et al. 2014) and apple (Darbyshire et al. 2013)
point to potential differences in how much chill accumulation beyond the minimum
chill requirement can impact heat accumulation necessary for bud break.
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Table 1 Database summary for parameterizing and validating data from Californian (CA, United States) and Spanish locations. Weather station descriptors are latitude, longitude, number of observation sites associated with each climatic station and mean distance between them are shown from Californian (www.cimis.water.ca.gov), and Spanish (www.ruralcat.net/web/guest/agrometeo.estaciones and redarexplus.gobex.es/RedarexPlus/) weather stations. CP, are the average value of the Chill Portions accumulated from October 1 to March 31 of the observation years.

<table>
<thead>
<tr>
<th>Location</th>
<th>Station name</th>
<th>Latitude (º)</th>
<th>Longitude (º)</th>
<th>Number of observations sites</th>
<th>Mean distance to observations (Km)</th>
<th>Observation years</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Valley (CA)</td>
<td>Manteca</td>
<td>37.83</td>
<td>-121.22</td>
<td>1</td>
<td>13</td>
<td>2009-2014</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Modesto</td>
<td>37.65</td>
<td>-121.19</td>
<td>1</td>
<td>13.5</td>
<td>2009-2011, 2013, 2014</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Kesterson</td>
<td>37.23</td>
<td>-120.88</td>
<td>1</td>
<td>18.5</td>
<td>2009-2014</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Oakdale</td>
<td>37.73</td>
<td>-120.85</td>
<td>1</td>
<td>7</td>
<td>2009-2014</td>
<td>57</td>
</tr>
<tr>
<td>North Coast (CA)</td>
<td>Santa</td>
<td>38.40</td>
<td>-122.80</td>
<td>1</td>
<td>8</td>
<td>2012-2015</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Rosa</td>
<td>38.53</td>
<td>-122.83</td>
<td>2</td>
<td>15.5</td>
<td>2007-2013, 2015</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Windsor</td>
<td>38.22</td>
<td>-122.35</td>
<td>3</td>
<td>1.5</td>
<td>2004-2011, 2014, 2015</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Carneros</td>
<td>38.43</td>
<td>-122.41</td>
<td>1</td>
<td>1.5</td>
<td>2010, 2012-2016</td>
<td>50</td>
</tr>
<tr>
<td>South Central Coast (CA)</td>
<td>San Benito</td>
<td>36.85</td>
<td>-121.36</td>
<td>1</td>
<td>2.5</td>
<td>2014</td>
<td>35</td>
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<tr>
<td>Spain</td>
<td>Nipomo</td>
<td>35.03</td>
<td>-120.56</td>
<td>1</td>
<td>16</td>
<td>2010, 2011, 2014-2016</td>
<td>47</td>
</tr>
<tr>
<td>Spain</td>
<td>Raïmat</td>
<td>41.68</td>
<td>0.45</td>
<td>1</td>
<td>5.4</td>
<td>2013</td>
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<tr>
<td></td>
<td>d’Anoia Badajoz</td>
<td>35.51</td>
<td>-6.39</td>
<td>1</td>
<td>0.5</td>
<td>2014-2016</td>
<td>59</td>
</tr>
</tbody>
</table>
Table 2 Example of model fit and performance for overlap estimates at one potential

Cr. AICc was used for evaluation of models for parameterization data set. R² and RMSE were used for evaluating the relation with observed and predicted bud break values applying fitted model parameters for parameterization and validation datasets. Only significant (p-value < 0.05) models are shown.

<table>
<thead>
<tr>
<th>Crr (CP)</th>
<th>Overlap (%)</th>
<th>Model parameters</th>
<th>Parameterization</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>β₁</td>
<td>β₂</td>
<td>β₃</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>6992</td>
<td>8152</td>
<td>0.0729</td>
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<td>7800</td>
<td>7751</td>
<td>0.0813</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>6110</td>
<td>9657</td>
<td>0.0463</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>2141</td>
<td>14041</td>
<td>0.0252</td>
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<tr>
<td>9</td>
<td>75</td>
<td>8856</td>
<td>11358</td>
<td>0.0636</td>
</tr>
</tbody>
</table>

AICc, Akaike Information Criterion; R², R-square; RMSE, Root Mean Square Error measured.
Table 3 Model fit and performance for chilling requirement estimates at the same 40% overlap. Evaluation of $R^2$ and RMSE for parameterization and calibration datasets evaluating the relation with observed and predicted bud break values applying fitted model parameters. With $p$-value < 0.05, all model fits were significant.

<table>
<thead>
<tr>
<th>$C_r$ (CP)</th>
<th>Overlap (%)</th>
<th>Model parameters</th>
<th>Parameterization</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\beta_1$</td>
<td>$\beta_2$</td>
<td>$\beta_3$</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>8591</td>
<td>9236</td>
<td>0.0833</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>7096</td>
<td>9242</td>
<td>0.0577</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>6110</td>
<td>9657</td>
<td>0.0463</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>2836</td>
<td>12225</td>
<td>0.0292</td>
</tr>
<tr>
<td>11</td>
<td>40</td>
<td>7275</td>
<td>8615</td>
<td>0.0662</td>
</tr>
</tbody>
</table>

$R^2$, R-square; RMSE, Root Mean Square Error measured
Figure 1 Location of the weather stations (red dots) used in the study in California (A) (USA) and Spain (B).
Figure 2 Chardonnay bud break day of the year subsets, ordered from earlier to later bud break observations, for parameterizing, P (42 observations, filled symbols) and validating, V (39 observations, open symbols) the Chill Overlap Model.
Figure 3 Drawing to explain the overlapping between the chill and heat phases implied in the Chill Overlap Model. $C_1$, $C_2$ and $C_3$ exemplify the different accumulation times for chill, and $H_1$, $H_2$ and $H_3$ the different accumulation times for heat. Rectangles with solid lines show fixed chill/heat amounts, and rectangles with dashed lines show not fixed chill/heat accumulated amounts. The overlap where additional accumulated chill (CP, Chilling Portions calculated with Dynamic Chill Accumulation Model) that reduce heat sum (GDH, Growing Degree Hour determined with GDH ASYMCUR Model) is when $C_a$, chill accumulated from $C_2$ to $C_3$, and $H_r$, heat accumulated from $H_1$ to $H_2$, are determined simultaneously for the same period.
Figure 4A Chill Overlap Model fit parameterization. Chill requirement ($C_r$) are 9 CP and an overlap of 40% between the chill accumulation ($C_a$) and the Heat Accumulation ($H_a$) phases. Model accuracy was evaluated with AICc obtaining a 346.62 value.
Figure 4B Predicted and observed bud break day of the year from the Chill Overlap Model using parameterizing data, obtaining $R^2=0.54$ and RMSE=8.86 days statistics. Fitted values were determined after 9 CP corresponding to the chill requirement ($C_r$) are meet, and an overlap of 40%.
Figure 5 Predicted and observed bud break day of the year evaluated with the best performance fit model parameters with the validating dataset, obtaining $R^2=0.69$ and RMSE=7.32 days statistics. 9 CP were the chill requirements ($C_r$), and 40 % the overlap.