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Research Article

Performance of a Chill Overlap Model for Predicting BudBreak in Chardonnay Grapevines over a Broad Range of Growing Conditions

Maria Teresa Prats-Llinàs,[1]* Theodore M. DeJong,[2] Katherine S. Jarvis-Shean,[3] Joan Girona,[1] and Jordi Marsal[1]

[1]Efficient Use of Water in Agriculture Program, Institut de Recerca i Tecnologia Agroalimentàries (IRTA), Parc de Gardeny (PCiTAL), Fruitcentre, 25003, Lleida, Spain; [2]Department of Plant Sciences, University of California Davis, One Shields Avenue-Mail Stop 2, CA 95616; and [3]University of California Cooperative Extension, Sacramento, Solano and Yolo Countries, 70 Cottonwood Street, Woodland, CA 95695.

*Corresponding autor (teresa.prats@irta.cat; tel: + 34 973032850 ext. 1592)

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Abstract: Predicting phenological stages through modelling has significant implications for planning viticultural practices and for predicting the impact of climate change on phenology. The Chill Overlap Model is based on an exponentially declining curve which integrates the demonstrated compensatory relationship between chill and heat accumulation. It also incorporates recent research-based knowledge of physiological changes during dormancy. The aim of this work was to develop parameters in order to create a Chill Overlap Model for predicting bud break in *Vitis vinifera* cv. Chardonnay grapevines. We also wanted to determine if using a Chill Overlap Model could be better at predicting bud break than previously developed

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phenology models. The Chill Overlap Model 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 timing determined in the Californian and Spanish wine grape-growing regions, which represent a wide range of climates, was used to establish the parameters for a Chill Overlap Model for Chardonnay. The newly developed Chardonnay Chill Overlap Model did not succeed in predicting bud break any better than previous models, but it did highlight significant differences between the dynamics of chilling in grapevines compared to other species on which a Chill Overlap Model had previously been employed. Further research is needed to account for the environmental and vineyard management factors that influence the timing of bud break in order to improve the model and to better understand factors that influence the completion of dormancy in grapevines.

Key words: chill and heat requirements, chill portions, dynamic chill accumulation model, modeling, 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 the impact of climate change on plant phenology and developing strategies to mitigate its possible effects on crop behavior (Chuine 2000, Richardson et al. 2013, Darbyshire et al. 2016).

Bud break in grapevines indicates the onset of vegetative growth (Duchêne et al. 2010). Any delay during this stage could have a significant impact on the seasonal growth cycle,

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making it a key phenological stage, with major site-to-site and cultivar variability (García de Cortázar-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, García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010, Duchêne et al. 2010, Nendel 2010). Even so, other factors have also been reported to modify grapevine phenology; these include 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 its release depends on the exposure of buds to winter chill to end the period of endodormancy, followed by a period of the spring heat that releases ecodormancy and triggers bud break (Caffarra and Eccel 2010, Pope et al. 2014). Chill and heat are needed to release the corresponding dormancy stages and this translates into specific temperature exposure requirements for different species and cultivars (Chuine 2000).

The grapevine growth models used to predict bud break are mainly based on the computation of heat accumulation during spring, which is also known as Thermal Time (Cannell and Smith, 1983), from a given date until a species-dependent threshold is reached. Under such models, which are referred to as Spring Warming models (Hunter and Lechowicz, 1992), the chilling requirements are assumed to be met every year (Pope et al. 2014). However, it has been observed that such models may be inappropriate for Mediterranean climates, which occasionally have mild winters in which the required minimum amount of chill may not be met (Pope et al. 2014), or for areas in which climatic conditions are tending to produce warmer winters

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(Luedeling and Brown, 2011). Other models, called sequential models, treat winter chill and spring heat accumulation as independent phases that are fulfilled sequentially (Kramer 1994).

Complex sequential models that have been developed for Chardonnay (*Vitis vinifera*) and some other grape cultivars, have provided knowledge about developmental responses to environmental drivers. Indeed, García de Cortázar-Atauri et al. (2009) developed the BRIN model by adding more biological and physiological explanations about grapevine crops to a phenological modelling framework. Theirs was the first grapevine model to predict bud break on the basis of physiological mechanisms as a framework for heat accumulation approaches. Caffarra and Eccel (2010) built the FENOVITIS model for the Chardonnay cultivar, 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).

In studies of deciduous trees, it is often assumed that chilling and heat accumulation requirements must be fulfilled one after another, up to a fixed threshold. However, this sequential fulfilment of the chill and heat requirements is often based on a very simplified understanding of the dormancy breaking processes (Luedeling et al. 2009). Measuring the specific periods in which 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 grapevines (Fila et al. 2014). Although it is known that specific proteins appear to contribute to the induction and release of bud dormancy, 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).

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Dormant buds undergo major changes when chilling requirements are fulfilled. These include changes to membranes and to the fatty acid ratios in their phospholipids (Faust et al. 1997). In fact, research has shown that the relationship between chilling, post-rest and bud break is complex. Following recent findings on genetic dormancy control (Horvath 2009, Leida et al. 2012), Pope et al. (2014) suggested that there could be a considerable overlap between chill and heat requirements. While working on peach (*Prunus persica*), it was observed that once the minimum chill requirement has been met, but before bloom occurs, there is a decreased expression of the genes responsible for the response to cold with continued chill exposure (Yamane et al. 2011).

Following these principles, recently developed Chill Overlap Models have attempted to integrate possible interactions between chill and heat accumulation. An exponential declining curve was fitted to describe the decreasing requirements for post-chill heat accumulation in response to prolonged exposure to chilling temperatures. This model contemplates a partial compensatory relationship between the chilling and post-chill heat requirements necessary to finally trigger bud break (Pope et al. 2014). Comparing the conceptual basis for this model with other recently developed models for Chardonnay may help to increase our understanding of the biological and physiological behavior of grapevines during the dormancy period. Chill Overlap Models have already been developed for deciduous almond (*Prunus dulcis*) and apple (*Malus domestica*) trees, and have shown significant improvements over previous prediction models (Pope et al. 2014, Darbyshire et al. 2016).

Furthermore, the chill overlap model calculates chill accumulation using the Dynamic chill accumulation model (Fishman et al. 1987). This chill accumulation model has been found to

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perform either better than, or at an equivalent level to other commonly used chill accumulation methods, when applied 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, which is imbedded in the Dynamic chill accumulation model, has not been previously tested for grapevines. It could, however, 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 to determine whether such a model would be capable of improving bud break prediction over a broad range of growing conditions. Bud break data from different grape-growing regions in California and Spain were used to develop and test the predictive capacity of the model. This was done using observations from a range of different locations so as to evaluate the reliability of the model under different climatic conditions.

Materials and Methods

Bud break and weather station data

Bud break data for the Chardonnay cultivar were used to parameterize and validate the performance of the Chill Overlap Model (Pope et al. 2014). Wineries and research institutions from different parts of California (USA) and Spain provided phenological data for different locations (Figure 1). Bud break was considered to have been achieved when 50 % of buds were open. However, it was not possible to apply a specific scale for all of the data sources so 50% bud break was estimated for some locations.

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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). In cases of missing temperature data at a specific station, equivalent data were used from the nearest weather station. In some cases, when several phenology observation sites were located near the same weather station (i.e. Windsor, Carneros), mean bud break data were calculated and used with temperature data taken from the same station.

Phenology data were divided into two independent parameterization (*n*=42) and validation (*n*=39) subsets. The criteria used for these datasets had representative climatic conditions for both subsets. Covering the most representative climatic conditions enabled testing the robustness of the model (Figure 2).

Description of the Chill Overlap Model

The Chill Overlap Model is based on an exponentially declining curve representing 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 accumulation was determined using the Dynamic model (Fishman et al. 1987) and involved a two-step process. In the first step, a chill intermediate was formed or destroyed

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according to an hourly bell-shaped temperature relationship. The formation of chill intermediates was enhanced in cold temperatures, with an optimal efficacy at 6-8 ºC, and the negation of previously accumulated chill intermediates if temperatures exceed a specific threshold (24ºC). In the second step, the chill intermediate was computed as a single Chill Portion (CP), which could not be negated by subsequent warmer temperatures. One Chill Portion (CP) is equivalent to a period of 30 hours of continuous chill exposure at ≤ 6ºC (Erez and Fishman 1998).

Heat accumulation was calculated using the Growing Degree Hour (GDH) ASYMCUR Model (Anderson et al. 1986). In line with the model described in Anderson et al. (1986), the acquisition of heat was taken as an hourly asymmetric curvilinear model defined by two cosine-type equations based on 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 was also tested with this model.

Hourly temperatures were required as inputs for the Dynamic chill accumulation and GDH ASYMCUR models. Daily maximum and minimum temperatures were then interpolated into hourly data following Linvill (1990) and the specific parameters of each weather station location were used for both the parameterization and validation datasets (Table 1).

The chilling requirement (C_r) is the minimum amount of accumulated chill required for bud break to occur, and the heat requirement (H_r) is the minimum amount of accumulated heat required for bud break to be possible. According to Pope et al. (2014), the C_r should be satisfied before any additional chill (C_a) modifies any specific part of the heat accumulation (H_a) phase and results in an overlap between the two phases. This is defined by Eq. (1) and shown in Figure 3:

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$$H_a = \beta_1 + \frac{\beta_2}{e^{(\beta_3 \, x \, C_a)}} \qquad (1)$$

H_a, heat accumulation from C_r to bud break

C_a, chill accumulation after C_r has been met

β_1, β_2 and β_3, model parameters

The β_1 model parameter, defined as the lowest heat accumulation required for bud break to be possible, is equivalent to H_r. In fitted models, it correlates with heat accumulation experienced in high chill years/climates. β_2 corresponded to the difference in heat accumulation between the highest and the lowest observation values ($\beta_2 = H_o - H_r$), which is estimated by data accumulated during mild winters. The β_3 parameter was related to the shape of the curve, based on values ranging between 0 and 1 that define this shape (Pope et al. 2014).

Development of model parameters and parameterization

The Chill Overlap Model parameters were fitted following Pope et al. (2014) and Darbyshire et al. (2016). The chilling requirement (C_r) had to be estimated, as no previous experiments had been 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 throughout the period for all sites and years (October 1 to March 31) was tested as the maximum C_r with 1 CP increments. According to our dataset, the range tested was from 1 to 31 CP (Spain - Sant Sadurni d'Anoia, 2012). The overlap interval values tested ranged from 10 % to 90 %, with increments of 5% (Figure 3).

For each C_r tested, the starting values used to fit the model parameters were estimated from parameterization datasets. The lowest value of H_a was used as an estimation of β_1. The

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difference between the highest and lowest H_a values was estimated as $\beta_2 = H_o - H_r$, and the starting value for β_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 the most appropriate fit values for the model. Negative values of β_1 and β_2 where dismissed based on them lacking biological sense: for example, heat accumulation cannot have negative values (Pope et al. 2014).

Evaluation of model parameters

Three indices were evaluated to obtain values for the model parameters. The information-theoretic approach Akaike Information Criterion (AIC_C) was used to make comparisons within each C_r, with the model with the lowest value of AIC_C following Burham and Anderson (2002). Models with different C_r values could not be compared because of the change in the response variable that resulted in lower C_r values associated with earlier heat accumulation (Pope et al. 2014). Candidate model parameters were also evaluated considering R^2 and Root Mean Square Error (RMSE) values. The models with the best parameters were evaluated in the same way, using the validation dataset.

Results

Selected candidate models prioritized according to the lowest AIC_C, highest R^2 and lowest RMSE values using parameterization data are presented 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

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to 31), an AIC_C with a value of 346.62, a R^2 of 0.54 and a RMSE of 8.86 were obtained with a C_r 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 β_1, β_2 and β_3, respectively (Table 2). An evaluation of the same overlap with different chilling requirements is presented in Table 3. Changing the C_r value from 9 CP did not improve the performance of the model.

These parameters were then validated 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, with a C_r of 9 CP and a chill-heat overlap of 40% resulting in an R^2 = 0.69 and an RMSE of 7.32 days (Table 2 and Table 3) (Figure 5). This indicates that the previously chosen model parameters were as valid as could be expected.

The analysis of model RMSE was most accurate for data from the Central Valley (CA), with values of 7.09 and 6.13 days, for parameterization and validation, respectively. Model performance was less accurate at warmer winter locations such as on the Central Coast (CA) (9.00 for parameterization and 10.00 days for validation) and the South Central Coast (CA) (10.60 for parameterization and 8.49 days for validation) (data not shown), possibly 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 the C_r, in locations where prolonged chill accumulation occurred, there was a decrease in the heat requirements

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needed to reach bud break. In contrast, in warmer locations, where less chill was accumulated, more heat was required to trigger bud break. In our study, cooler conditions resulted in a later bud break (in Spain), while warmer conditions produced an earlier bud break (the Central Coast and South Central Coast California locations) (Table 1). A delay in the induction of dormancy attributable to high temperatures has been previously reported for Chardonnay (Caffarra and Eccel 2010). This suggests that mild fall temperatures may contribute to earlier dormancy, whereas warm temperatures, above 20ºC, may delay it (Caffarra and Eccel 2010). During the same period, it was reported that low temperatures led to a more rapid chill accumulation in Chardonnay, and therefore to an earlier ecodormancy transition (Cragin et al. 2017).

The parameterizing dataset seemed to provide sufficient data, including extreme values, to estimate C_r, H_o and H_r and consequently fit the model parameters. The estimated parameters presented some differences between the starting values and the fitted parameters (data not shown). According to the interpretation of the model parameters (Pope et al, 2014), the lower the fitted β_3 value is, the more linear the relation between C_a and H_a will be. As a consequence, the value of β_1 should be lower and the value of β_2 should be higher. This was not, however, true of all the cases analyzed in the current study (Table 2, Table 3). These discrepancies were difficult to explain by the curved relationship between chill and heat, particularly considering the numerous studies that have shown this relationship in temperate perennial species (Chuine 2000, Harrington et al. 2010). Given this failure to find an appropriate model, it is recommended to experimentally determine the value of C_r and to fit the values directly, rather than trying various different 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 models used with

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fruit trees, it is necessary to add endodormancy break dates. This should then yield more robust projections of phenological changes (Chuine et al., 2016).

Model performance

The Chill Overlap Model which was developed with this research did not substantially improve the accuracy of bud break prediction compared to previously phenological models developed for the Chardonnay cultivar, under specific locations and climatic conditions (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010). However, compared to the Chill Overlap Model developed for other species, these models were able to improve previous models accuracy (Pope et al. 2014 and Darbyshire et al. 2016). Improving model accuracy was not the first objective of this work, while our aim was to evaluate if the Chill Overlap Model could improve the understanding of the processes involved during dormancy to bud break transition. In this study, the data used for model development covered a wider geographical area for the Chardonnay cultivar than in previous studies and this may have been one reason for its only modest level of accuracy.

The variations in phenological data sources may also have been an important reason for the limited accuracy of the model developed, given that the criteria for determining the exact onset of bud break was not uniform across sites and locations. Although bud break was generally considered to take place when 50 % of buds were open, determining the exact day of bud break likely varied depending on the number of days between observations and the person who was collecting the data. In addition, the weather data were not recorded directly adjacent to the vines whose phenology was being observed. Therefore there may have been differences between the temperatures recorded at the weather stations and those experienced in the vineyards, particularly

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in the case of differences in altitude (Nendel 2010) (Table 1). Furthermore, it should be noted that maximum and minimum daily temperature data were used to estimate hourly chill and heat accumulation. The use of actual mean hourly temperatures would have been more accurate for determining temperature accumulation but these data were not available for all sites.

Clonal behavior may change depending to location, being mainly affected by microclimates and soils (Fidelibus et al. 2006, Jones et al. 2014). Since in our study Chardonnay clones were not identified in all locations, we should consider clones as a possible source of variability difficult to evaluate in this analysis.

The variability in phenology at a given location may be explained by microclimatic differences (Verdugo et al. 2016). This could affect phenological development as a consequence of specific changes in environmental conditions at a very local level. In the California region, for example, phenology performance may have been affected by microclimate differences in the Central Valley and especially in the North Coast regions where there can be strong local differences in air movement (Figure 4B, Figure 5). Another important factor may have been the distance between the weather stations and the observation vineyards (Table 1). Although the Central Valley (CA) region is characterized as being flat, the distance between the sites and weather stations could have been more than 10 km, and this could have been a significant source of error in model performance.

Air temperature has been widely reported to be the main driver of phenology. Depending on net radiation, the differences between air and bud temperature may be 0.5 – 2ºC, but on foggy days this relationship changes to ~0.1 – 0.2 ºC (Itier et al. 1987). Fog tends to reduce bud temperature and to therefore increase chill accumulation. However, the incidence of fog

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formation is highly variable on a year-to-year basis, being the result of many complex and conditional meteorological factors. The general trend in the California region has been for a decrease in the number of winter fog events, which tend to be characterized by sustained periods with air temperatures below 7ºC. Possible consequences of there being less fog include warmer air and an increase in direct sun exposure, which amplifies warming and reduces chill accumulation (Baldocchi and Waller 2014).

Orchard management may also potentially influence microclimates through effects associated with canopy management, cover cropping and the irrigation regime (Luedeling et al. 2009). Grapevine management practices, for example, have been reported to influence the completion of bud break. In post-harvest irrigation experiments, cutting off irrigation early has been reported to advance the bud break stage with the Perlette cultivar (Williams et al. 1991). Similar responses were observed in an experimental vineyard of Chardonnay grown at Raïmat, Lleida, Spain, during Spring 2016 (J. Marsal personal communication). Late pruning slightly delayed bud break in 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 are not initiated until there has been sufficient chilling to break endodormancy, after which bud growth will respond to warm temperatures. Over a range of temperatures, chill accumulation in grapes was evaluated to be most efficient at 2.8 ºC (Caffarra and Eccel 2010). A recent study conducted with Chardonnay canes indicated that three weeks of exposure to temperatures of -3 ºC was also effective for releasing endodormancy (Cragin et al. 2017). The Dynamic chill model,

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which was used to evaluate chill accumulation in the Chill Overlap Model, considered 6-8ºC to be the optimum temperature range for chill accumulation. This model also considers the effects of negation of chill associated with a period with temperatures above 20ºC. To the best of our knowledge, the dynamic chill model had not previously been used to test grapevine species (Dokoozlian 1999). Even though the chill models described in the literature are often not comparable because the accumulated chilling units differ from site to site, previously tested chill models and the experiments performed on grapevines provide some basis for comparisons (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010). The dynamic chill accumulation model seemed to be the most appropriate one for measuring chill in this study because of the range of climates present in the dataset.

For most plants, 10 ºC is considered the best base temperature for growth. According to Williams et al. (1985), 10 ºC is an appropriate base temperature for calculating heat accumulation to predict grapevine development, although several other reports indicate that a lower base temperature may be more appropriate for predicting bud break (Duchêne 2010). A base temperature of near 5 ºC has been found appropriate for bud break prediction in two studies (Moncur et al. 1989, García de Cortázar-Atauri et al. 2009).

In this study, the Growing Degree Hour (GDH) ASYMCUR Model (Anderson et al. 1986) was used to determine heat accumulation, considering a base temperature of 4ºC. A base temperature of 10ºC during the endodormancy release period was also tested, but no improvements in model prediction capacity were achieved. It therefore seems that a base temperature of below 10ºC may be suitable for predicting bud break, indeed, this has been used

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in previously developed models for working with the Chardonnay cultivar (García de Cortázar-Atauri et al. 2009).

As the goal of this research did not include determining threshold temperature values for chill and heat accumulation, we used published threshold values. Further research is clearly needed to evaluate temperatures for the perception of chill and heat by buds during dormancy, but due to other limitations on the dataset used in this study, it was not appropriate to pursue that objective. Other factors may also affect the perception of chill and heat temperature by buds such as the lack of synchrony in bud growth with apical buds opening before lateral due to their heat requirements having been met earlier (Martin et al. 2000) and differences in bud vigor and in the amounts of carbon and nitrogen reserves (Ben Mohamed et al. 2010).

In this study Chardonnay was found to need ~9 CP compared to 13, 21 and 23 CP, respectively, for the Sonora, Mission and Nonpareil almond cultivars (Pope et al. 2014), and 34 CP for the Crips Pink apple cultivar (Darbyshire et al. 2016). Eshghi et al. (2010) reported that, compared with other deciduous fruit crops, grapevines grown in Iran do not have very high chilling requirements and need relatively little exposure to chill. Our results were consistent with this report. Considering that 1 CP is equivalent to 30 hours of continuous chill at 6ºC (Erez and Fishman 1998), the chilling requirement evaluated for Chardonnay may have been similar to a chill exposure of 270 hours (9 CP x 30 hours/CP). Previous research using chill hours accumulated between 0 and 10 ºC found that 200 hours was the minimum chilling exposure required for normal grape bud growth for the Perlette cultivar (Dokoozlian, 1999) and that 336 hours at temperatures below 6ºC were required for Cabernet Sauvignon (Botelho et al. 2007).

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Although there is no exact equivalence between Chill Hour and Chill Portion quantification, as they are not constant in time or space; it is reassuring that the differences between species in terms of chill requirements (C_r) are consistent with different chill models, and accentuate biological differences between species. Some studies have suggested that the Dynamic chill accumulation model is most accurate for quantifying winter chill, and understanding location-specific and year-to-year variability and that it performs best in warmer areas (Luedeling et al. 2009).

Differences among species can be highlighted by comparing the values of the Chill Overlap Model parameters. In addition to the low chill requirement of grapevines, the overlap defined by the period with a compensatory relationship between the chill and heat requirements appeared to be smaller in grapevines (40 %) than in almonds and apples (75 %) (Pope et al. 2014 and Darbyshire et al. 2016). As hypothesized by Pope et al. (2014), the amount of overlap may vary according to the plant species. Grapevines, for example, appear to have less need for chill than other species, even during the compensatory stage between the two requirements. On the other hand, although having only a low chill demand, Chardonnay appeared to require the perception of more heat, as shown in the β_1 fitted model parameter. This suggests that grapevines could 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 has been met in both species, cool locations with considerable accumulations of chill and subsequent decreases in heat demand produce later observations of bud break in grapevines, but earlier bloom in apples. In warmer locations, more

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heat was required to meet bud break conditions and grapevines reached bud break earlier, while with apples, additional time was need to reach flowering, with this stage being delayed (Darbyshire et al. 2016).

Values of β_3 defined similar curves of roughly the same shape, but with different chill and heat requirements from species to species. Additionally, a more precise estimation of chilling requirements, obtained by forcing or through growth-room experiments, could increase model curvature (Dennis 2003, Pope et al. 2014). A previous study demonstrated that models calibrated with growth room data provided a good level of 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). Addition of other factors, such as the time of pruning, into the models may also improve their performance (Martin and Dunn 2000).

More research is needed to improve the accuracy and utility of phenology models. For example, it would be valuable to be able to predict the potential impact of climate change on the suitability of using specific grape cultivars in some future growing regions. The results of the Chill Overlap Model for the Chardonnay grapevine did not significantly improve bud break predictions compared to simpler phenological models previously developed for the same cultivar (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010). However, the fact that the model attempted to integrate the overlapping effect of chill accumulation on the subsequent heat accumulation, which has been empirically observed in the field, shows that it would be worthwhile to try to improve the model. This could be done by accounting for several of the sources of potential non-temperature related variability in bud break highlighted in this work.

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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 provides a framework for analyzing 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 the potential sources of inaccuracy in the data sets used. Knowledge of the possible influences of environmental factors and management practices at specific locations should help to reduce inaccuracies in the predictions obtained and lead to further model improvement.

The study also confirmed the apparent low chill requirement of Chardonnay and the fact that temperatures below 10ºC seemed to be effective in fulfilling its chill requirement. On the other hand, the study supported Chardonnay's need to receive substantial amounts of warmth to achieve bud break. These factors need to be considered for understanding how increases in temperature 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 our understanding of plant physiology and crop behavior during dormancy and bud break. Even though all the phenological models present simple interpretations to predict complex realities, this model is sufficiently complex and does not require expensive experiments to evaluate its performance.

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Table 1 Database summary for parameterizing and validating data for Californian (CA, United States) and Spanish locations. Weather station descriptors are latitude, longitude, altitude, number of observation sites associated with each weather station and the mean distance between them. Data are shown for Californian (www.cimis.water.ca.gov) and Spanish (www.ruralcat.net/web/guest/agrometeo.estacions and redarexplus.gobex.es/RedarexPlus/) weather stations. Average bud break data are provided for the different observation years. CP is the average value for the Chill Portions accumulated in the observation years from October 1 to March 31. Daily average maximum (T_{max}) and minimum (T_{min}) temperatures are from October 1 to March 31.

	Weather stations										
Location	Station name	Latitude (º)	Longitude (º)	Altitude (m)	Number of observations sites	Mean distance from observations (Km)	Observation years	Bud break (DOY)	CP	T_{max} (°C)	T_{min} (°C)
Central Valley (CA)	*Manteca*	37.83	-121.22	10	1	13	2009-2014	80	55	17.9	4.5
	Modesto	37.65	-121.19	11	1	13.5	2009-2011, 2013, 2014	85	57	21.4	6.2
	Kesterson	37.23	-120.88	23	1	18.5	2009-2014	79	52	23.8	5.5
	Oakdale	37.73	-120.85	50	1	7	2009-2014	77	57	22.8	7.6
North Coast (CA)	*Santa Rosa*	38.40	-122.80	24	1	8	2012-2015	85	46	21.0	4.5
	Winsdor	38.53	-122.83	92	2	15.5	2007-2013, 2015	82	55	21.3	4.8
	Carneros	38.22	-122.35	2	3	1.5	2004- 2011, 2014, 2015	74	55	21.0	6.1
	Oakville	38.43	-122.41	58	1	1.5	2010, 2012-2016	78	50	22.6	6.7
Central Coast (CA)	*San Benito*	36.85	-121.36	104	1	2.5	2014	65	35	20.8	4.6
South Central Coast (CA)	*Nipomo*	35.03	-120.56	78	1	16	2010, 2011, 2014-2016	61	47	19.4	8.8
Spain	*Raïmat*	41.68	0.45	286	1	5.4	2013	95	49	13.9	3.8
	Sant Sadurni d'Anoia	41.43	1.79	164	1	5	2006, 2012, 2014, 2015	92	42	18.7	6.6
	Badajoz	35.51	-6.39	188	1	0.5	2014-2016	76	59	22.3	8.8

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Table 2 Example of model fit and performance for overlap estimates at one potential *Cr*. AIC_C was used to evaluate the models used for the parameterization data set. R^2 and RMSE were used to evaluate the relationship between the observed and predicted bud break values by applying fitted model parameters for parameterization and validation datasets. Only significant (p-value < 0.05) models are shown.

C_r (CP)	Overlap (%)	*Model parameters*			*Parameterization*			*Validation*	
		β_1	β_2	β_3	AIC_C	R^2	*RMSE (days)*	R^2	*RMSE (days)*
9	25	6992	8152	0.0729	352.28	0.53	9.45	0.68	7.87
9	30	7800	7751	0.0813	359.77	0.47	10.33	0.64	9.50
9	40	6110	9657	0.0463	346.62	0.54	8.86	0.69	7.32
9	50	2141	14041	0.0252	400.53	0.56	16.78	0.62	16.44
9	75	8856	11358	0.0636	386.61	0.44	14.17	0.42	14.47

AIC_C, Akaike Information Criterion; R^2, R-square; RMSE, Root Mean Square Error measured.

Table 3 Model fit and performance for estimates of the chilling requirement with the same 40% overlap. Evaluation of R^2 and RMSE for parameterization and calibration datasets evaluating the relation between the observed and predicted bud break values by applying fitted model parameters. All the model fits were significant, with p-value < 0.05.

C_r (CP)	Overlap (%)	*Model parameters*			*Parameterization*		*Validation*	
		β_1	β_2	β_3	R^2	*RMSE (days)*	R^2	*RMSE (days)*
7	40	8591	9236	0.0833	0.48	11.67	0.49	11.72
8	40	7096	9242	0.0577	0.48	10.80	0.65	8.84
9	40	6110	9657	0.0463	0.54	8.86	0.69	7.32
10	40	2836	12225	0.0292	0.60	12.63	0.61	11.78
11	40	7275	8615	0.0662	0.55	10.17	0.61	9.99

R^2, R-square; RMSE, Root Mean Square Error measured.

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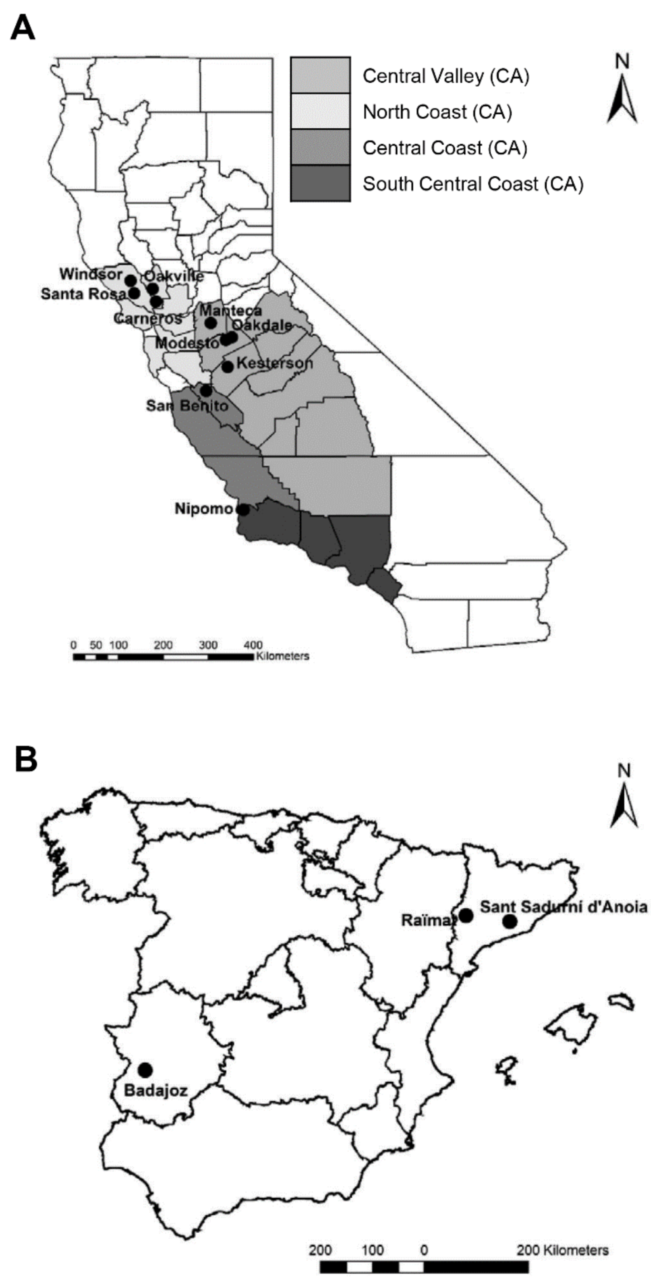

Figure 1 Location of the weather stations (red dots) used in the study in California (**A**) (USA) and Spain (**B**).

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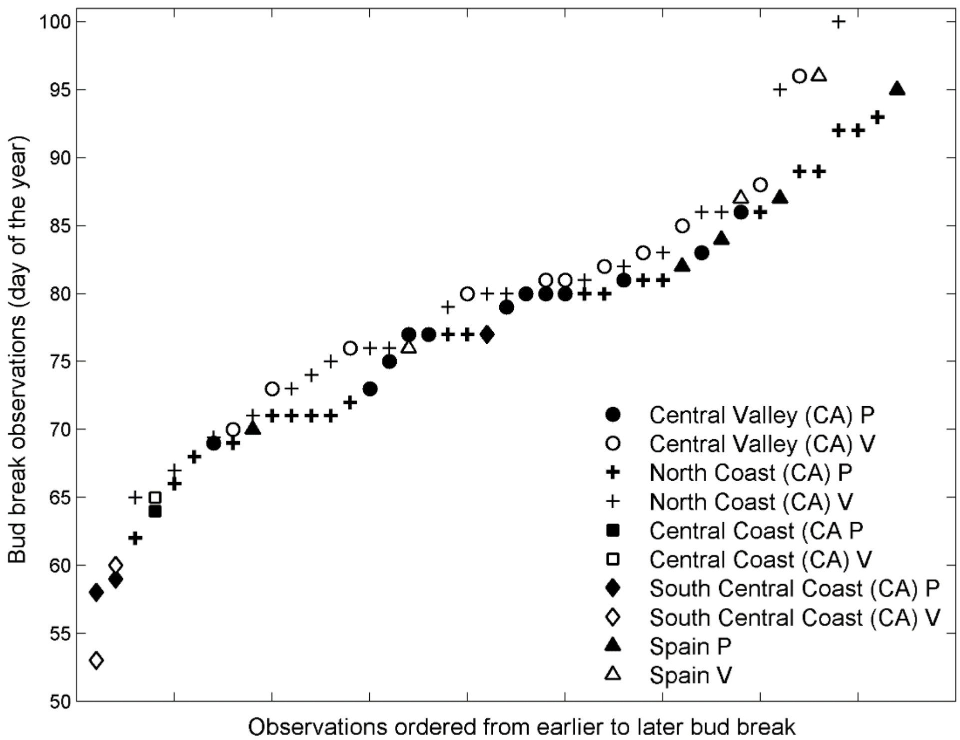

Figure 2 Day of the year bud break subsets for Chardonnay, ordered from earliest to latest bud break observations, used for parameterizing: P (42 observations, filled symbols), and validating: V (39 observations, open symbols) the Chill Overlap Model.

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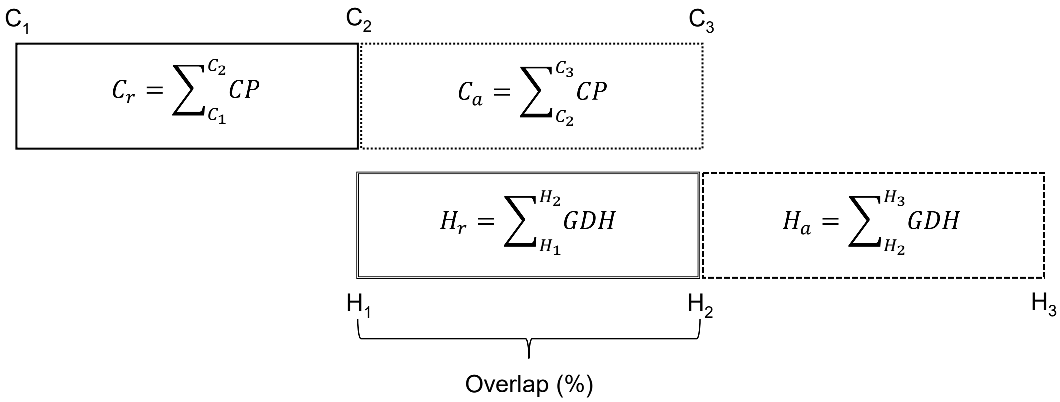

Figure 3 Explanation of the overlap between the chill and heat phases implied in the Chill Overlap Model. C_1, C_2 and C_3 exemplify the different accumulation times for chill, while H_1, H_2 and H_3 show the different accumulation times for heat. The rectangles with solid lines show measures of fixed chill/heat, and the rectangles with dashed lines show variable amounts of accumulated chill/heat. The overlap where the additional accumulated chill (CP, Chilling Portions calculated with Dynamic Chill Accumulation Model) reduces the heat sum (GDH, Growing Degree Hour determined with GDH ASYMCUR Model) occurs 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.

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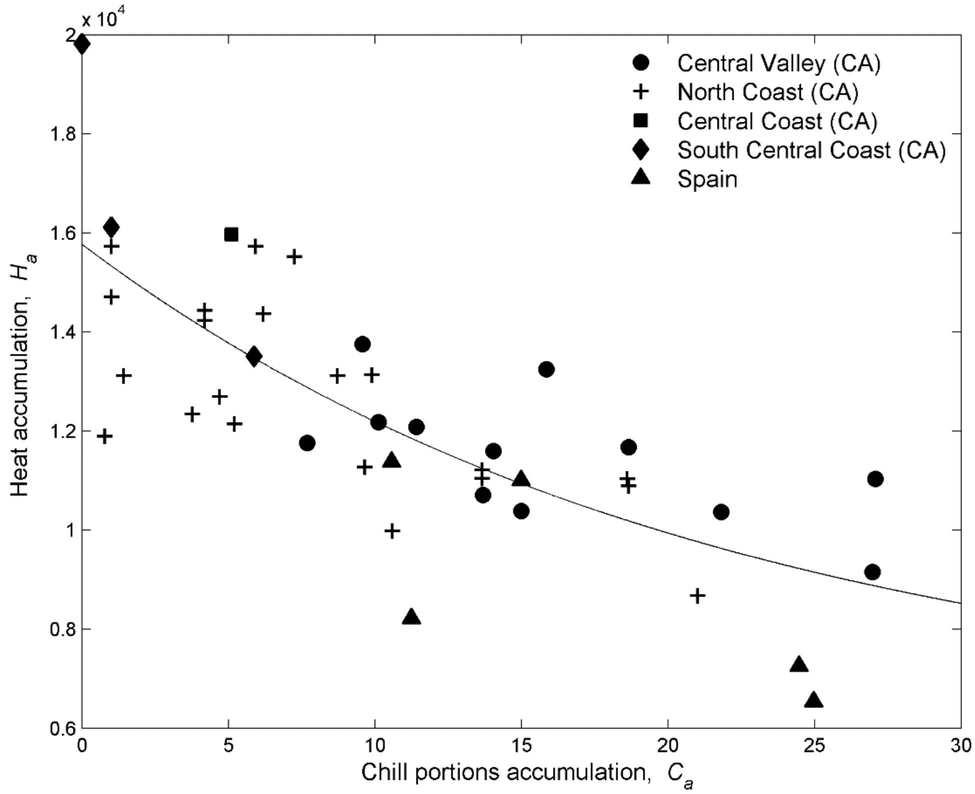

Figure 4A Chill Overlap Model fit parameterization. The chill requirement (C_r) was 9 CP and an overlap of 40 % between the chill accumulation (C_a) and the heat accumulation (H_a) phases. Model accuracy was evaluated at an AIC_C value of 346.62.

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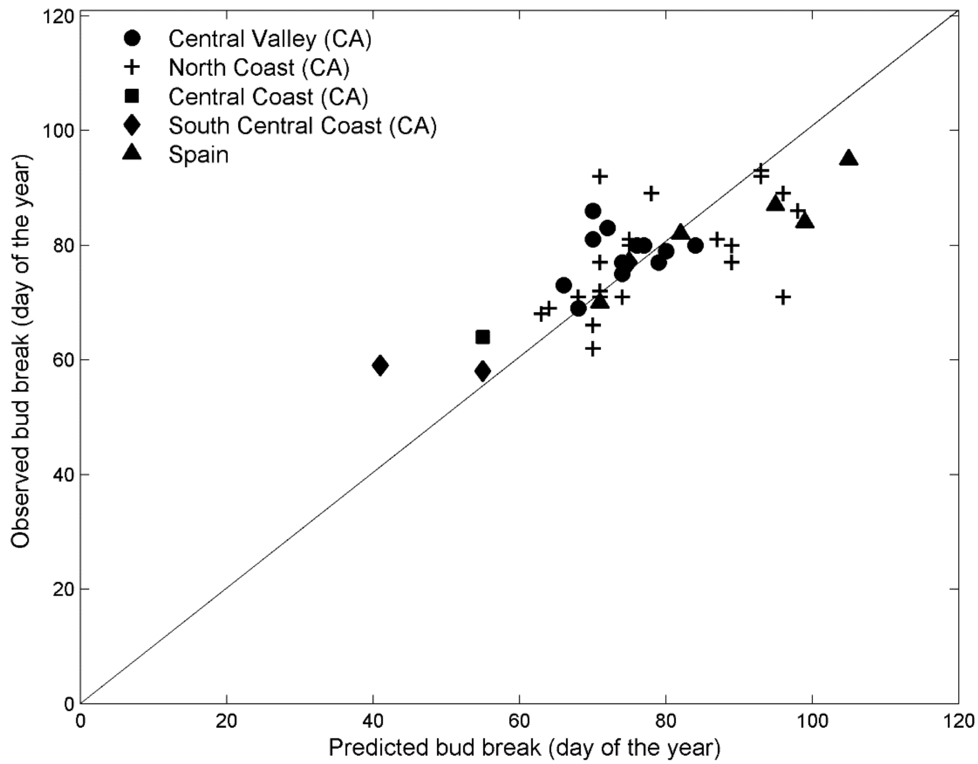

Figure 4B Predicted and observed bud break day of the year based on the Chill Overlap Model using parameterization data (R^2=0.54 and RMSE=8.86 days). The fitted values were determined after 9 CP corresponding to the chill requirement (C_r) were met, with an overlap of 40 %.

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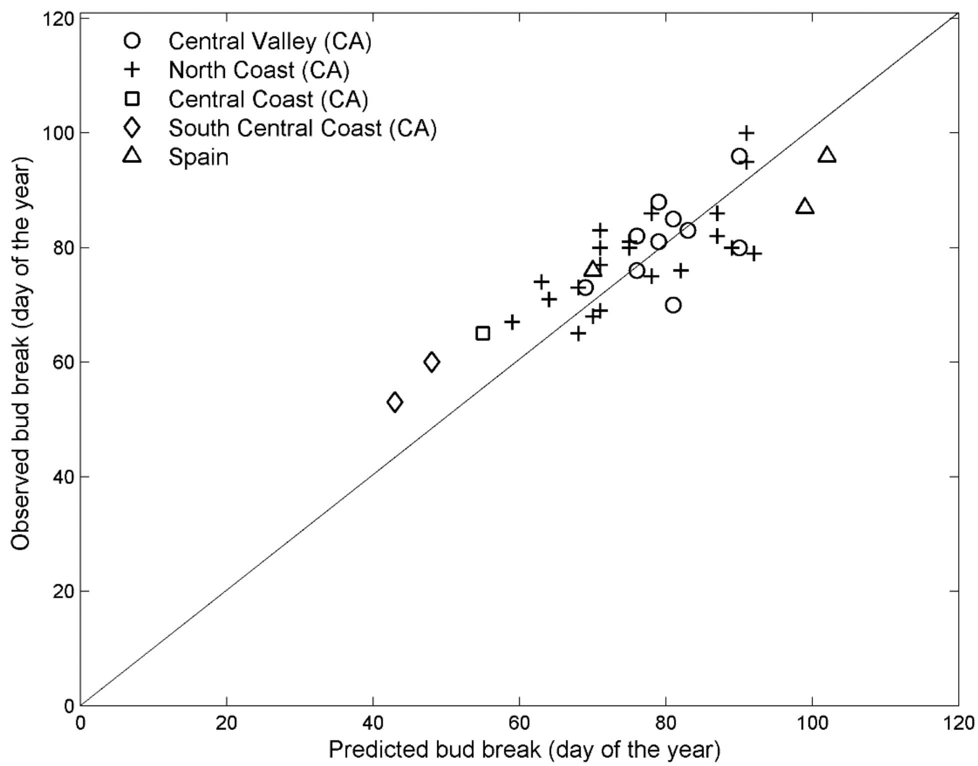

Figure 5 Predicted and observed bud break day of the year evaluated with the best performance fit model parameters using the validating dataset (R^2=0.69 and RMSE=7.32 days). The chill requirement (C_r) was 9 CP, with a 40 % chill/heat overlap.