PHENOLOGICAL MODEL PERFORMANCE TO WARMER CONDITIONS: APPLICATION TO PINOT NOIR IN BURGUNDY

Cédric CUCCIA[1], Benjamin BOIS[1,2], Yves RICHARD[1], Amber Kaye PARKER[3,4], Iñaki GARCIA DE CORTAZAR-ATAURI[5], Cornelis VAN LEEUWEN[4,5] and Thierry CASTEL[1,6,*]

1: Centre de Recherches de Climatologie / Biogéosciences UMR 6282 CNRS / Université de Bourgogne, 6 Bd Gabriel, 21000 Dijon, France
2: Institut Universitaire de la Vigne et du Vin « Jules Guyot », Université de Bourgogne, 1 rue Claude Ladrey, 21000 Dijon, France
3: The New Zealand Institute for Plant & Food Research Limited, Lincoln, Private Bag 4704, Christchurch Mail Centre, Christchurch 8140, New Zealand
4: Bordeaux Sciences Agro, ISVV, Ecophysiology and Functional Genomics of Grapevines, UMR 1287, F-33140 Villenave d'Ornon, France
5: INRA, US1116 AGROCLIM, F- 84014 Avignon, France
6: Département 2A2E AgroSup Dijon, 21000 Dijon, France

Abstract

Aim: The current work aims to assess the performance of two phenological models - a linear model (*Grapevine Flowering Véraison* model, *GFV*) and a curvilinear model (*Wang and Engel* model, *WE*) - to warmer temperature conditions for the grapevine variety Pinot noir in Burgundy.

Methods and results: Simulations using historical data from the 1973-2005 period were similar between models and consistent with observations. To mimic potential climate warming for 2050 and 2100, 3 °C and 5 °C were added to each daily average temperature of the 1973-2005 dataset. The results showed that the two models simulated similarly the véraison stage of Pinot noir in Burgundy for temperature increases up to 5 °C. However, the simulation by the *GFV* model was 4.7 days earlier than that by the *WE* model when 10 °C was added. This difference may reflect the inhibitory effect of high temperatures on plant development incorporated in the equations of the *WE* model. Finally, both models were tested for three other sites in Europe (Carcassonne, Cagliari and Seville) with quite contrasting climatic conditions. Results obtained showed that both models differed significantly when they were applied at latitudes below 40°N.

Conclusion: In cool-climate grape growing regions and for early grapevine varieties, increased temperatures (up to +5 °C) may advance the date of véraison as predicted by heat summation models but produce little difference in predictions between the simpler *GFV* model and the *WE* model.

Significance and impact of the study: Both models (*GFV* and *WE*) satisfactorily reproduce the observed véraison dates for Pinot noir in Burgundy. For the range of temperature increases expected in the future for cool temperate areas, a model that uses a curvilinear response to temperature does not improve significantly the phenological predictions compared with a simple model based on a linear response.

Key words: climate change, phenological model, Pinot noir, Burgundy, *Vitis vinifera*

Résumé

Objectif: Ce travail vise à évaluer, pour le cépage Pinot noir en Bourgogne, la sensibilité de deux modèles phénologiques - un modèle linéaire (modèle '*Grapevine Flowering Véraison*', *GFV*) et un modèle curviligne (modèle de *Wang et Engel*, *WE*) - quand ils sont utilisés avec une gamme de températures plus chaudes.

Méthodes et résultats: Pour le climat actuel, les stades phénologiques simulés par les deux modèles sont conformes aux observations. Afin de mimer le réchauffement climatique aux horizons 2050 et 2100, 3 °C et 5 °C ont été ajoutés aux températures moyennes quotidiennes enregistrées sur la période 1973-2005. Les résultats montrent que les deux modèles simulent de façon similaire les dates du stade de véraison du Pinot noir en Bourgogne jusqu'à un réchauffement de 5 °C. Par contre, pour un réchauffement de 10 °C la simulation de la date de véraison avec le modèle *GFV* est en moyenne 4.7 jours plus précoce qu'avec le modèle *WE*. Cette différence peut s'expliquer par l'effet inhibiteur des températures élevées sur le développement des plantes qui est intégré dans les équations du modèle *WE*. Les deux modèles testés dans trois autres sites en Europe (Carcassonne, Cagliari et Séville) avec des conditions climatiques assez contrastées montrent une divergence importante aux latitudes inférieures à 40°N.

Conclusion: Dans les régions viticoles au climat frais et pour des cépages précoces, une augmentation des températures (jusqu'à 5 °C) ne montre pas de différences significatives entre les deux types de modèle phénologique testés (linéaire et curviligne).

Signification et impact de l'étude: Les deux modèles (*GFV* et *WE*) permettent de reproduire correctement les dates de véraison observées pour le Pinot noir en Bourgogne. Pour l'amplitude du réchauffement attendu en climat tempéré frais, l'utilisation d'un modèle simple basé sur une réponse linéaire à l'augmentation des températures est suffisante afin de prédire l'évolution des dates des stades phénologiques.

Mots clés: changement climatique, modèle phénologique, Pinot noir, Bourgogne, *Vitis vinifera*

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*Corresponding author: thierry.castel@u-bourgogne.fr

INTRODUCTION

Temperatures in France have significantly increased during the 20th century (Moisselin *et al.*, 2002). Climate projections suggest that they could rise by 3 to 5 °C during the 21st century (IPCC, 2007). For Burgundy, recent projections (using the Weather Research and Forecasting (WRF) regional climate model) of the SRES-A2 scenario have shown an increase up to 3 °C for 2030-2050 and 5 °C by the end of the century (Xu *et al.*, 2012). Several studies suggest that increased temperatures due to climate change will highly impact the growth and yield of crops (Olesen *et al.*, 2011). Much of the decline in yield is due to shorter crop durations at these warmer temperatures (Wheeler *et al.*, 2000). Some studies, based on observations (Duchêne and Schneider, 2005; Jones and Davis, 2000) or simulations (Brisson and Levrault, 2010; Hannah *et al.*, 2013; Webb *et al.*, 2007) of grapevine growth stages, have shown significant advances in phenology and some have indicated a delay in budburst due to insufficient chilling requirements (Webb *et al.*, 2007). Various models have been used to simulate grapevine development rate and phenology (Bindi *et al.*, 1997a; Bindi *et al.*, 1997b; Caffarra and Eccel, 2010; Chuine *et al.*, 2004; García de Cortázar-Atauri *et al.*, 2009; Parker *et al.*, 2011; Riou, 1994). Other studies have assessed the responses of grapevine phenology in a climate change context (Duchêne *et al.*, 2010; Webb *et al.*, 2007).

The response of grapevine to temperature is often described by linear or non-linear heat summations (Gladstones, 1992): linear models use a sum of temperatures above a base temperature from a fixed day of the year or previous phenological stage to the appearance of the next phenological stage (Hall and Jones, 2010); non-linear models include a temperature threshold (optimal temperature) above and below which plant development is limited or at its maximum or minimum rate (García de Cortázar-Atauri *et al.*, 2010). For non-linear models, Beta models are generally used to describe in a more mechanistic way the non-linear relationship between temperature and crop development rate (i. e., physiological process efficiency) within the thermal kinetic window (Yin *et al.*, 1995). Such linear and non-linear models are often calibrated using phenological observations from a single site (Duchêne *et al.*, 2010) or from a collection of sites (García de Cortázar-Atauri *et al.*, 2009; Parker *et al.*, 2011) but may not cover the full range of climate conditions encountered by a given grapevine variety worldwide. Consequently, models might be used beyond their calibration limits, especially when they are applied to future warmer climate conditions. Hence, the date of a phenological stage, estimated with the climate projections for the 21st century, may differ according to the type of linear and non-linear phenological model that is applied. This question is critical to adapt viticulture to climate change, and to our knowledge it has not been yet fully addressed in previous studies. Various approaches exist for the simulation of possible future global warming. One approach is dynamic or statistical downscaling using Regional Climate Models (RCM) (White *et al.*, 2006; Xu *et al.*, 2012), empirical functions (Jones and Alves, 2012) or climate generators (Webb *et al.*, 2007). All of these methods require additional uncertainty analysis to produce relevant patterns of temperature. Their performances have already been discussed elsewhere (Huth *et al.*, 2003; Teutschbein *et al.*, 2011).

The present work evaluates the performance of two types of phenological models, *Grapevine Flowering Véraison* (*GFV* – a simple linear temperature summation model (Parker *et al.*, 2011; Parker *et al.*, 2013) –

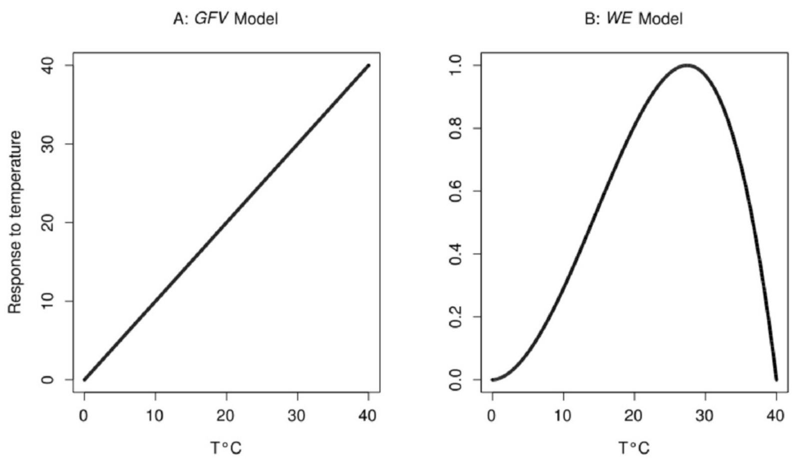

Figure 1. Daily response of plant development to temperature between 0 and 40 °C for the linear Grapevine Flowering Véraison (A) and curvilinear Wang and Engel (B) models.

Figure 1A) and *Wang and Engel* (*WE* – a non-linear model first proposed for wheat crop by Wang and Engel (1998) – Figure 1B), parameterized for *Vitis vinifera* L cv. Pinot noir under a range of different temperature conditions. The aims were 1) to assess whether the models were able to accurately simulate the observed véraison dates for Pinot noir in Burgundy from the original historical records of 1973-2005, 2) to assess whether the performance of the models under warmer conditions was significantly different in Burgundy and 3) to compare the results from increased temperature scenarios in Burgundy with three other sites of different temperature profiles under warmer temperature conditions.

MATERIALS AND METHODS

1. Véraison data for Pinot noir

Phenological observations were collected by the Service Régional de l'Alimentation (SRAL) in Savigny-lès-Beaune (France, 47°3'N – 4°49'E, 267 m above sea level (asl)). The database contained the date when 50 % véraison (Stage 85 of the BBCH scale, 2001) was observed (referred to as "véraison" herein) for Pinot noir for each year of the 1973-2005 period (Figure 2A), excluding the following five years for which no values were measured: 1982, 1987, 1995, 2000, and 2001. The observation site, also located in Savigny-lès-Beaune, was close to the meteorological site (~100 m).

2. Observed climate data and scenario design for climate warming

Daily minimum and maximum temperature measured in Savigny-lès-Beaune between January 1 1973 and December 31 2005 (hereafter referred to as "original temperature dataset") was collected from the French national (Météo France) meteorological station network (Cuccia, 2013). The daily mean temperature was calculated as the arithmetic mean of the minimum and maximum daily temperature (Figure 2B).

To investigate warmer climate conditions, we increased the temperature by adding a constant temperature shift on a daily time step to existing temperature datasets (Asseng *et al.*, 2013). Three temperature scenarios were considered: +3 °C and +5 °C to daily mean temperatures, which represent realistic increases for the second half of the 21st century (IPCC, 2007; Xu *et al.*, 2012); +10 °C, which represents extreme conditions (unlikely over the 21st century – Terray and Boé, 2013).

Furthermore, the impact of these three scenarios on both phenological models was tested for three different sites in Europe (ECA temperature series (Klein Tank *et al.*, 2002)): Carcassonne (France – 43°12'N – 02°18'E, 126 m asl), Cagliari (Italy – 39°14'N – 9°03'E, 21 m asl) and Seville (Spain – 37°25'N – 5°52'W, 34 m asl). These three sites offer a wide range of annual mean temperatures to compare and contrast with Savigny-lès-Beaune: 11.3 °C (Savigny-lès-Beaune), 13.9 °C (Carcassonne), 16.9 °C (Cagliari) and 18.8 °C (Seville).

3. Phenological models

The *GFV* and *WE* models were tested against the original temperature dataset and the three temperature-shifted datasets using parameters from their previous calibrations (García de Cortázar-Atauri *et al.*, 2010; Parker *et al.*, 2011).

The *GFV* model computes the linear response of Pinot noir to temperature by the two equations described below (see also Figure 1):

$$S_f(t_s) = \sum_{t_0}^{t_s} R_f(x_t) \geq F^* \qquad (1)$$

$$R_f(x_t) = GDD(x_t) = \begin{cases} 0 & \text{if } x_t < T_b \\ x_t - T_b & \text{if } x_t \geq T_b \end{cases} \qquad (2)$$

where S_f is the state of forcing, t_0 is the 60th Day of Year (DOY), t_s is the véraison date, R_f is the rate of forcing, *GDD* is the Growing Degree Day, x_t is the average of the minimum and maximum (mean) temperature for day t, F^* is equal to 2511°C, which is the value calculated for Pinot noir in Parker *et al.* (2013), and T_b is the base temperature (0 °C). This simple model only uses average temperature data as input with no action threshold on grapevine development at high temperatures. Hence, it is implicitly assumed that grapevine development is optimal even at temperatures above 40 °C.

The *WE* model adapted for grapevine and parameterized for Pinot noir by García de Cortázar-Atauri *et al.* (2010) takes into account three cardinal temperatures: a temperature optimum bounded by two threshold temperature values corresponding to minimum and maximum temperature below and above which no action on the plant is considered. The model computes the rate of phenological development of the grapevine in response to temperature by weighted forcing units (Chuine *et al.*, 2013) where the rate of thermal summation $C(T_t)$ falls in the range from 0 to 1 and follows a Beta curve (equation 3, i. e., bell-shaped – Figure 1):

$$F^* = \sum_{t_0}^{t_s} C(T_t)$$

$$C(T_t) = \begin{cases} \frac{2(T_t - T_{min})^A (T_{opt} - T_{min})^A - (T_t - T_{min})^{2A}}{(T_{opt} - T_{min})^{2A}} \\ 0 \end{cases}$$

$$\begin{aligned} &\text{if } T_{min} < T_t < T_{max} \\ &\text{if } T_t < T_{min} \text{ or } T_t > T_{max} \end{aligned} \quad (3)$$

with the A parameter of equation (3) given by:

$$A = \frac{log2}{log\left[\frac{T_{max} - T_{min}}{T_{opt} - T_{min}}\right]} \quad (4)$$

where $C(T_t)$ corresponds to the temperature action on grapevine development by day, t_s is the véraison date, T_t is the temperature for the day t and t_0 is the day when temperature action accumulation starts. Véraison occurs when the forcing units accumulation is equal or greater than the threshold F^*. The following parameter values were fixed according to those obtained by García de Cortázar-Atauri *et al.* (2010): $F^* = 89.2$ is the number of forcing units calculated for Pinot noir, t_0 = the 74[th] DOY (March 15), $T_{min} = 0$ °C (minimum temperature), $T_{max} = 40$ °C (maximum temperature) and $T_{opt} = 27.4$ °C (optimal temperature).

4. Assessment of models' performance

Model performance was assessed by the Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (x_{a,i} - x_{b,i})^2}{N}} \quad (5)$$

where x_a = observed day of véraison, x_b = simulated day of véraison and N = number of observations. The determination coefficient (R^2) was also used to identify the percentage of common variability between observations and simulations as well as between the two models.

Both models were applied on the 26-years (1973-2005 period) of observed climate data. The 26 simulated véraison dates were compared to the 26 véraison dates recorded in Savigny-lès-Beaune. A robust Bayesian estimation was used to test the significance of the average difference in mean véraison dates between the two models. The Bayesian estimation was based on Bayesian posterior probability distribution, which evaluates whether the probability of a difference may be too small to matter. This was assessed using the 95 % Highest Density Interval (HDI - Kruschke, 2013), which is a useful summary of the probability that the true value lies within the HDI. The values of the 95 % HDI bounds are used to define the 95 % confidence interval.

RESULTS

1. Simulated versus observed véraison for Savigny-lès-Beaune

The performance of the simulation models using the original temperature records (1973-2005) are summarized in Table 1. For both models, 62 to 65 % of differences between observed and simulated véraison dates fell within the range of -5 and +5 days (Figure 3). There was no difference ($p<0.05$) between the models for the dataset: the simulated mean DOY using the original temperature data was 228.1 for the *GFV* model and 227.9 for the *WE* model (Figure 4); the RMSE was 5.7 days for the *GFV* model and 5.8 days for the *WE* model; and the R^2 was 0.81 for the *GFV* model and 0.84 for the *WE* model. For both models, estimated véraison dates were later than

Table 1. Statistical analysis of the performance of the Grapevine Flowering Véraison (*GFV*) and Wang and Engel (*WE*) models using the original 1973-2005 dataset.

	GFV model	*WE* model
R^2	0.81	0.84
RMSE (days)	5.7	5.8
Underestimated values (%)	57.7	61.5
Overestimated values (%)	34.6	27
Simulated values = Observed values (%)	7.7	11.5
Over RMSE (%)	27	31
RMSE before DOY 240 observations	4.6	5.2
RMSE after DOY 240 observations	8.9	8.4

R^2, determination coefficient; RMSE, root mean square error; DOY, day of year

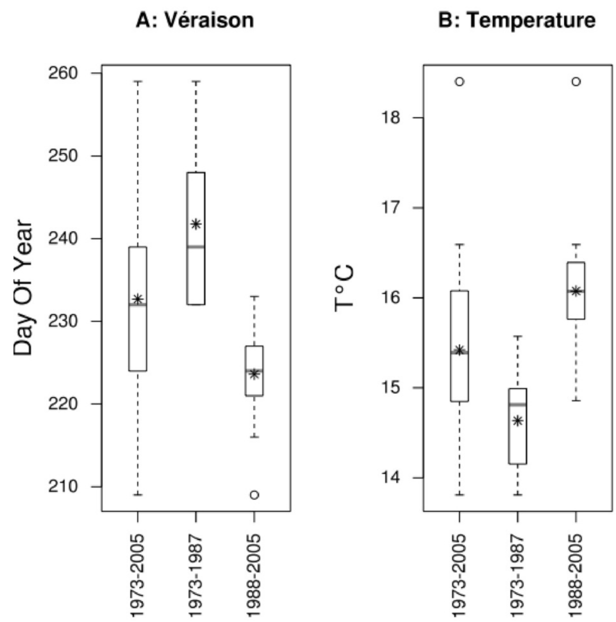

Figure 2. Box and whisker plot (gray line: median and black asterisk: mean) of (A) annual observed véraison dates for the whole period (1973-2005) and sub-periods (1973-1987 and 1988-2005) for Savigny-lès-Beaune weather station and (B) average mean temperature from March to September. Open circles represent the year 2003.

originally observed for almost 60 % of the dataset. This bias was particularly strong in years with late véraison (i. e., colder years). The performance of both models was significantly reduced after DOY 240 (August 28 – vertical dashed line in Figure 3); pre-DOY 240 RMSE values were 4.6 and 5.2 days and post-DOY 240 RMSE values were 8.9 and 8.4 days for the *GFV* and *WE* models, respectively.

2. Model simulations under warmer climate conditions

The simulated DOY for véraison were similar ($p>0.05$) for both models in response to warmer temperature scenarios of +3 °C (average DOY = 206.9 and 206.6 for *GFV* and *WE*, respectively) and +5 °C (average DOY = 195 for both models) (Figure 4).

For the +10 °C scenario, there was a significant difference of 4.7 days ($p<0.05$) between the two models (average DOY = 172.7 for the *GFV* model and 177.5 for the *WE* model). However, the difference between model simulations (4.9 days) was marginal compared to the advance in véraison caused by this +10 °C temperature shift (55.4 days earlier).

Inter-annual variability of the véraison dates was reduced as temperature increased. For simulations with the original temperature dataset (1973-2005), the maximum difference between the earliest and latest dates of véraison ranged from 40 days for the *GFV* model to 42 days for the *WE* model (Figure 4). For warmer scenarios, these ranges were reduced to 30 and 28 days (+3 °C), 28 and 22 days (+5 °C) and finally 18 and 15 days (+10 °C), respectively for the *GFV* and *WE* models (Figure 4). The variances for both models were very similar when they were applied either to original or artificially increased temperature data up to +5 °C (data not shown). With a 10 °C positive shift, the variance was more reduced for the *WE* model than for the *GFV* model.

3. Temperature threshold for *WE* simulations

Figure 5 presents the day to day spread (boxplot of the 26-year historic dataset) of temperature action for the *WE* model with original data and the +10 °C scenario data. The simulations for the original temperature data (light gray curve) showed a sigmoid shape in response to forcing temperatures; however, even during the warmest part of the summer (DOY 200 to 230, late July to mid-August), the temperature actions of *WE* barely reached 1 with the original temperature data. With the +10 °C scenario (10 °C added to the daily observed temperature), the temperature actions often reached the optimum value (= 1) from mid-spring (around DOY = 125, early May) to late June (DOY = 175) when véraison occurred. The temperature actions started to decline during summer (daily average temperature often exceeded 27.4 °C, the optimum temperature), when véraison had already occurred (Figure 5).

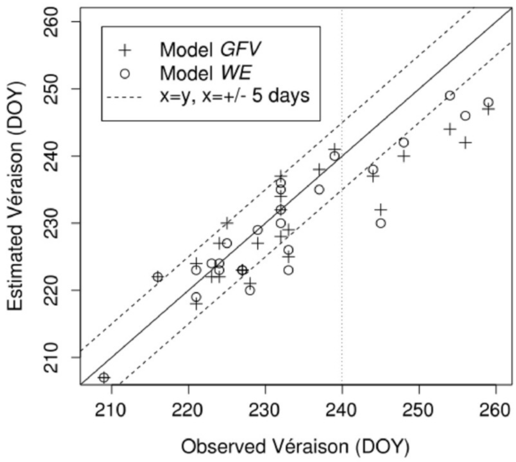

Figure 3. Estimated versus observed véraison Day of Year (DOY) for the Grapevine Flowering Véraison (cross) and Wang and Engel (open circle) models. Upper and lower dashed lines indicate delays of +/- 5 days between observed and simulated véraison date, respectively. The vertical dashed line corresponds to DOY 240.

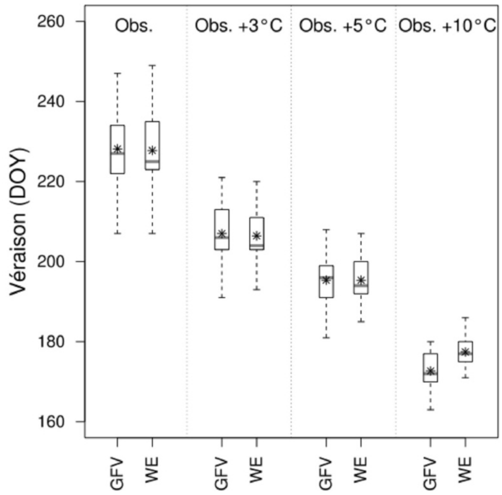

Figure 4. Boxplot (gray line : median and black asterisk : mean) of simulated véraison dates by the Grapevine Flowering Véraison (GFV) and Wang and Engel (WE) models for measured temperature data (Obs.) and +3 °C, +5 °C and +10 °C temperature scenarios. Each boxplot represents 26 values (26 years ; 1973-2005) ; véraison day corresponds to the Day of Year (DOY).

4. Comparison of the *WE* and *GFV* models among grape growing regions

When the difference in mean véraison dates between model simulations was calculated and compared between different grape growing regions along a latitudinal gradient from Dijon (47.3°N) - Carcassonne (43.2°N), Cagliari (39.2°N) down to Seville (37.3°N), results were similar for three of the four geographical places (Seville was the exception) up to the +5 °C scenario. Seville had a greater difference between simulations for all temperature scenarios (+3, +5 and +10 °C). For the +10 °C scenario, the differences between models were significant irrespective of the location (Figure 6). Moreover, we systematically observed an advance of the véraison date independent of the model and the site (data not shown).

DISCUSSION

The aim of this work was to assess the performance of two different phenological model types (*GFV* model – linear and *WE* model – non-linear) for predicting véraison under current and future climate conditions in Burgundy, using the method of increasing mean surface temperatures by a constant temperature increase (+3, +5 and +10 °C). When using the original temperature dataset up until 2005, both models accurately simulated véraison for Pinot noir in Burgundy. Although the RMSE value of approximately 6 days that was obtained for these simulations might be considered as large, it is smaller (1.5 to 2 days less) than those calculated during the calibration and validation phases of both models (García de Cortázar-Atauri *et al.*, 2010 ; Parker *et al.*, 2011).

The inter-annual variations of temperature actions were reduced during spring for the *WE* model (with values close to 1), which is not the case using uncapped degree day models (the warmer the temperature, the higher the temperature actions). Bell-shaped models like the *WE* model as well as bilinear capped models like the Biologically Efficient Degree Days (as proposed by Gladstones, 1992) reduce the inter-annual variability of véraison dates in a stronger way than uncapped degree day models do when temperatures increase. The models' performance may also change when integrating chilling effects on the starting date of heat summation such as proposed by several authors (Caffarra and Eccel, 2010 ; García de Cortázar-Atauri *et al.*, 2009).

Model parameters of the *WE* and *GFV* models were not calibrated to our data in this study, because we consider that the original parameterization of these models, based upon large datasets within which a great diversity of genetic and climate features are found, offers more robustness, especially when testing their responses to huge variations of temperature. It does not exclude the possibility of clonal variation

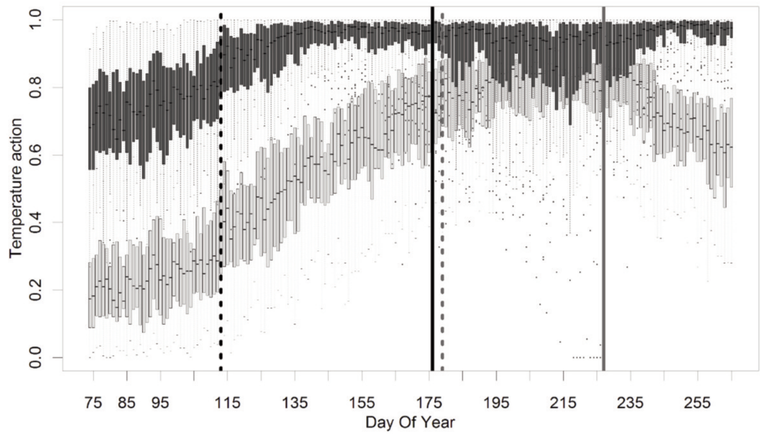

Figure 5. Boxplot of the daily action of temperature for the Wang and Engel model for the 1973-2005 period. Light gray boxes represent daily temperature action using the original historical temperature dataset. Dark gray boxes represent the daily temperature action for the +10 °C scenario. Vertical solid/dashed lines (light gray for the historical temperature dataset, dark gray for the +10 °C scenario) indicate the mean véraison date and the date above which temperature action is >0.8 (i. e., approaching optimal). Vertical solid lines (light gray for the historical temperature dataset, dark gray for the +10 °C scenario) indicate the mean véraison date for the 1973-2005 period.

resulting in slightly different F^* values. However, given that the models performed well compared with the observed data, the model simulations were considered satisfactory. Predictions were less accurate for dates of véraison later than DOY 240. This may represent an upper limitation for Pinot noir when using fixed start dates for modelling phenology, which may not correspond entirely to development phases, rather than using the date of a prior phenological event (i. e., in cooler years, thermal accumulation starts before the variety has actually reached certain development stages it would have reached in 'normal' years).

For the end of the 21st century, simulations indicate a maximum increase in temperature of about 5 °C (IPCC, 2007). The *GFV* model satisfactorily simulated véraison under our +5 °C temperature scenario, indicating that this simple linear temperature summation would be adequate in these future climate conditions for Pinot noir in Burgundy. Therefore, although the *WE* model may be more plausible mechanistically, this result indicates that climate change studies addressing warming impacts on grapevine phenology based upon uncapped degree day summations (e.g., Duchêne *et al.*, 2010; Nemani *et al.*, 2001) are comparable to those based upon more mechanistic models (Caffarra and Eccel, 2011; García de Cortázar-Atauri *et al.*, 2010) considering a null or negative effect of elevated temperature increases on phenological development.

The choice to add a constant temperature shift on a daily time step to increase temperatures enabled a simple method to emulate warmer temperature conditions and then compare the two models' performance. The limitation of this approach are: 1) it keeps the same temperature variability and may therefore not capture subtle differences in maximum and minimum temperature profiles that may occur with climate change and 2) it may create upper limits on plausible future climate scenarios. This is an area of interest for future research, which would require the accurate combination of high resolution numerical climate models with phenological model predictions. However, for this study, as indicated above, the models performed satisfactorily at +3 and +5 °C scenarios.

The significant difference between both models with an unrealistic very warm climate (+10 °C) suggests that with the *WE* model, the optimum temperature is exceeded, reducing the development rate of grapevine. This difference may reflect the inhibitory effect of high temperatures on plant development incorporated in the equations of the *WE* model. As the parameters used for the *WE* model could be considered close to physiologically relevant temperatures (Buttrose, 1969; Zufferey *et al.*, 2000), having an optimum temperature value close to 30°C, it is likely that similar results would have been reached with other early grapevine cultivars, for similar climatic conditions. Further studies need to be carried out to support this hypothesis as well as to assess the response of both temperature-based models used in this study with later parameters (i. e., later cultivars).

Model responses may differ for Pinot noir in other geographical regions. For latitudes above 40°N, the

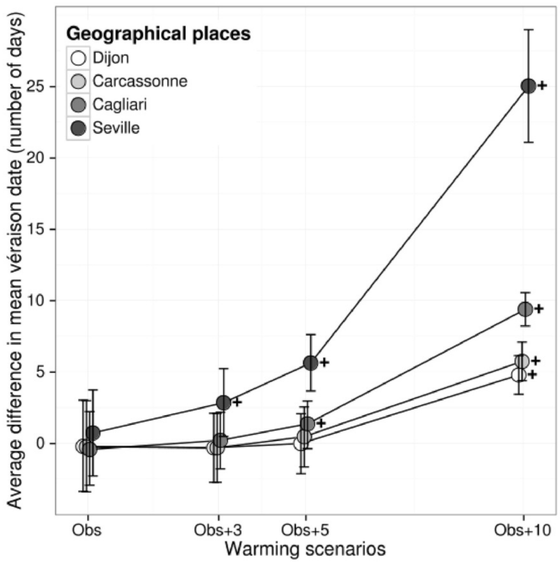

Figure 6. Evolution of the average difference (WE - GFV) in mean véraison date predicted by the two models as a function of the warming scenarios and for four different geographical places following a latitudinal gradient from 47.3°N (Dijon) to 37.3°N (Seville). The difference in means and the 95 % Highest Density Interval (HDI – vertical error bars) are derived from a robust Bayesian estimation following the method described in Kruschke (2013). 95 % HDI is a useful summary of where the bulk of the most credible values falls. Note that the values with a black cross (+) indicate that the difference is significant, i. e., the 95 % HDI interval does not include zero (no difference between models).

GFV and *WE* models produced similar predictions of véraison dates even for a warming up to +5 °C. For geographical places below 40°N latitude (Seville and Cagliari), significant differences associated with a more pronounced shift appeared between the *GFV* and *WE* model predictions. The *GFV* model was developed with the objective to create a model that can predict both flowering and véraison and to use this model to classify many varieties. Therefore, the limitations of this approach are: 1) the use of a single set of parameters for all the varieties, that is not optimized for each phenological stage of each variety and 2) a common start date must be used to compare varieties and needs to be a calendar day of the year rather than a prior development stage; therefore, the start date DOY = 60 may not correspond well in warmer climates (e.g., Seville) or under warmer climate conditions (+5° or +10° scenarios) where development may be too advanced relative to the model start date.

The +10 °C scenario at sites below 40°N indicated that results may also differ with other cultivars especially under extremely high temperature conditions or for late ripening cultivars or geographical regions. In future research, inter-annual temperature variability of the future climate may also need to be assessed. Finally, other factors could affect grapevine growth in warmer climate conditions, particularly the dynamics of water and nitrogen stress (Celette and Gary, 2013; Pellegrino *et al.*, 2006). In the future, crop models need to consider not only direct effects like advanced phenology but also indirect effects of climate change on grapevine growth and development (Dai *et al.*, 2009; Valdés-Gómez *et al.*, 2008).

CONCLUSION

Considering the range of projected warming for the 21st century, the results show that the phenological model choice should have no effect on véraison date simulations for Pinot noir in Burgundy. The same conclusion can be made for Pinot noir in warmer places (i. e., southern Europe) above 40°N. The linear temperature summation used in the *GFV* model diverged substantially from the *WE* model for very high temperatures (over 40 °C and the +5 °C and +10 °C scenarios) which may be encountered in the near future for more southern locations (i. e., below latitude 40°N), while inter-annual variability decreased for both models in warmer conditions. The *GFV* model is a suitable phenological model choice to address warming impact on early grapevine cultivar such as Pinot noir grown at northern latitudes above 40°N such as Burgundy.

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