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Adaptation to climate change by determining grapevine cultivar differences using temperature-based phenology models

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ABSTRACT

Grapevine phenology is advancing with increased temperatures associated with climate change. This may result in higher fruit sugar concentrations at harvest and/or earlier compressed harvests and changes in the synchrony of sugar with other fruit metabolites. One adaptation strategy that growers may use to maintain typicity of wine style is to change cultivars. This approach may enable fruit to develop under temperature conditions similar to those typically associated with that wine style. We demonstrate that Grapevine Flowering Véraison (GFV) and the Grapevine Sugar Ripeness (GSR) models can be implemented as a means of testing the suitability of alternative cultivars as an adaptation strategy to climate change.

Previous viticulture temperature-based models were reviewed and compared with the GFV and GSR models. The results from the original GFV and GSR models were combined to evaluate the classification of the 20 most represented cultivars. The GFV and GSR models were tested for three new historic and contrasting datasets: 31 cultivars in the VitAdapt collection, Bordeaux; Chardonnay, Champagne; and Sauvignon blanc, Marlborough. Errors of predictions were less than a week for flowering and véraison, and within 7-10 days for the time to reach relevant target sugar concentrations for these datasets. Future GFV and GSR projections for Chardonnay resulted in an advance at a rate of one to two days per decade for flowering and véraison, and two to five days per decade for time to 170 g/L sugar concentration for RCP 4.5 and 8.5 respectively.

Therefore, the GFV and GSR models are highly accurate and easy-to-use temperature-based phenological models for predicting flowering, véraison and time to target sugar concentrations when tested under new conditions. The models can be applied for characterising new cultivars, and assessing thermal time to flowering, véraison and different sugar targets. They can be used to assess cultivar performance in winegrowing areas worldwide under current or future climate conditions. The classifications therefore enable growers and researchers to compare the phenology of cultivars in a region today and to consider adaptation options: selecting later ripening cultivars or choosing alternative sites in the context of climate change.

KEYWORDS

grapevine, phenology, flowering, véraison, sugar, temperature, model, climate change, adaptation, classification

INTRODUCTION

Phenology has been identified as the key biological indicator of climate change (Menzel *et al.*, 2006) and an essential biodiversity variable (Pereira *et al.*, 2013), not only for the grapevine, but also for species worldwide. Grapevine phenology and harvest dates have been reported to have advanced worldwide in response to increasing temperatures due to climate change (Duchêne and Schneider, 2005; Petrie and Sadras, 2008; Webb *et al.*, 2007; Webb *et al.*, 2012). With earlier ripening, increased sugar concentrations have been observed at harvest and compressed harvests, as well as at early harvests to maintain target sugar concentrations (Jones and Davis, 2000; Duchêne and Schneider, 2005; Petrie and Sadras, 2008; Webb *et al.*, 2007; Webb *et al.*, 2012; van Leeuwen and Darriet, 2016). Due to advances in phenology and sugar accumulation, changes in synchrony between fruit development and other metabolites occur (Sadras and Moran, 2012). This can lead to unbalanced berry composition (e.g., sugar concentrations too high, acidity too low, and aromatic expression dominated by cooked fruit aromas) (van Leeuwen and Seguin, 2006; van Leeuwen *et al.*, 2019), and changes in wine style. To avoid this scenario, adaptation strategies that manipulate ripening to retain balance in primary and secondary metabolites need to be considered. In some cases, this may mean changing to later ripening cultivars (van Leeuwen *et al.*, 2019).

Historically, climate suitability was assessed via bioclimatic indices such as the Huglin Index or the Winkler Index (Amerine and Winkler, 1944; Huglin, 1978). While these indices are very useful for characterising the general climate of a given region, and for determining suitability for grapevine production, they do not accurately reflect the plant response to temperatures. In contrast, grapevine phenological models better represent plant response to the thermal environment, predicting the time of a phenological event based on air temperature, the key environmental factor driving phenology (Webb *et al.*, 2007; Parker *et al.*, 2011; Morales-Castilla *et al.*, 2020). Different grapevine cultivars have different temperature requirements to reach key phenological stages; earlier developing cultivars have lower temperature requirements compared with later ripening cultivars for the appearance of key phenological events. Therefore, understanding the temperature requirements of different cultivars using temperature-based phenological modelling can provide us with information about cultivar suitability to changing temperatures. This ultimately enables growers to adapt to climate change by changing to cultivars that may be more suited to future warmer conditions.

In order to understand potential cultivar phenology differences in response to temperature, it is necessary to develop and apply phenological models to characterise key phenological stages. The Grapevine Flowering Véraison (GFV) model was developed to characterise a wide range of cultivars based on the thermal times at which flowering and véraison occur; 95 and 104 grapevine cultivars for flowering and véraison respectively, have been characterised using this model (Parker *et al.*, 2011; Parker *et al.*, 2013). The GFV model is a linear model that starts accumulating thermal time from the 60th day of the year in the Northern Hemisphere (base temperature of 0 °C) until the appearance of the phenological stage (50 % flowering or véraison). Recently, the Grapevine Sugar Ripeness (GSR) model was developed (Parker *et al.*, 2020) which characterises the thermal time to six different target sugar concentrations (170, 180, 190, 200, 210, 220 g/L) for 65 cultivars. This temperature-based model starts on the 91st day of the year in the Northern Hemisphere, or on 1 April (base temperature of 0 °C) (Parker *et al.*, 2020).

A few studies have investigated the application of these models to new sites under current climate conditions and future climate scenarios, or to cultivars not currently characterised by the model. Cuccia *et al.* (2014) used the GFV model to predict the time of véraison for Pinot noir in the Burgundy region for future conditions with temperature increases of up to +5 °C. Parker *et al.* (2014b) and Parker *et al.* (2015b) conducted some preliminary evaluations of GFV model performance for Sauvignon blanc flowering in the Marlborough region, New Zealand, reporting predictions varying by 0-10 days between different sites. van Leeuwen *et al.* (2019) predicted the date of harvest at target sugar concentrations for Merlot, Cabernet-Sauvignon, Cabernet franc and Sauvignon blanc in Bordeaux for the periods 1951-1980 and 1981-2010, and found that the GSR model accurately predicted the time of sugar targets compared with the historical observations. They also used this model to predict the suitability of these cultivars to retain current ripening windows into the future, and found that Merlot and Sauvignon blanc would ripen earlier than the desired ripening window by 2050, with a + 1°C temperature increase over this period.

Wang *et al.* (2020) obtained good results using the GFV model for Cabernet-Sauvignon, Merlot, Cabernet franc and Chardonnay, across five regions in China: Changli, Laixi, Shangri-La, Xiaxian and Yanqi. The authors found that the practice of burying vines in the soil created a systematic bias in GFV predictions of flowering, although this effect was partially eliminated at véraison. However, this study had few data points and further evaluation may be required. Recently, de Rességuier *et al.* (2020) and Verdugo-Vásquez *et al.* (2019) used the GFV model to characterise phenology at the site scale. Since their development, testing of both models at new sites for historic and future predictions has been limited to the above studies. Similarly, the models have not been tested against other cultivar collections, which may include cultivars not previously characterised by the two models.

In this study, we carried out a review of bioclimatic indices and phenological models developed and tested for the grapevine, demonstrating the interest in and prevalence of the different modelling approaches. The application of the GFV and GSR models was evaluated for three new historic and contrasting datasets: the VitAdapt cultivar collection in Bordeaux, where up to 31 cultivars have been monitored for phenology and sugar accumulation; a long-term historic dataset from Champagne (1961-2019); and a dataset from the Southern Hemisphere for Sauvignon blanc, Marlborough. Future projections were also generated for Chardonnay at Champagne (RCP 4.5 and 8.5 emission scenarios). We demonstrate through these applications that the GFV and GSR models are highly accurate and easy-to-use for flowering, véraison and harvest date/target sugar concentration predictions for a wide range of cultivars, for both long term past climate data and future projections, and that they can be used successfully to assess how ‘early’ or ‘late’ cultivars may be for these key stages.

MATERIALS AND METHODS

1. Review of relevant literature

The objective of this review was to evaluate temperature-based approaches to characterising and understanding differences in grapevine

TABLE 1. Search terms applied to the WoS database.

Search number	Combined searches	Search terms	Number of publications retrieved
1		TS = (grape* AND temperature* AND phenolog*)	444
2		TS = (grape* AND classification AND phenolog*)	57
3		TS = (grape* AND temperature* AND bioclimat*)	62
4		TS = (grape* AND phenolog* AND model*)	299
5		TS = (grape* AND cultivar* AND temperature* AND phenolog*)	100
6		TS = (grape* AND variet* AND temperature* AND phenolog*)	127
7		TS = (grape* AND cultivar* AND phenolog* AND model*)	61
8		TS = (grape* AND variet* AND phenolog* AND model*)	89
9	5 & 6 (OR)		203
10	7 or 8 (OR)		132
11		TS = (grape* AND bioclimat* AND temperature* AND model*)	29
12		TS = (grape* AND variet* AND temperature* AND phenolog* AND model*)	57
13		TS = (grape* AND cultivar* AND temperature* AND phenolog* AND model*)	40
14	12&13 (OR)		88
15		TS = (grape* AND temperature* AND bioclimat* AND phenolog* AND model* AND classification AND variet*)	2
16		TS = (grape* AND temperature* AND bioclimat* AND model* AND classification AND cultivar*)	0
17		TS = (grape* AND temperature* AND phenolog* AND model* AND classification AND variet*)	6
18		TS = (grape* AND temperature* AND phenolog* AND model* AND classification AND cultivar*)	4
19	17 & 18 (OR)		9[2]

[1]TS = Topic search; the use of the search truncation “*” enables the following terms to be considered: grape* = grape, grapevine, grapes, cultivar* = cultivar, cultivars, variet* = variety, varieties, bioclimat* = bioclimate, bioclimatic, phenolog* = phenology, phenological, model* = model, models, temperature* = temperature, temperatures.
[2]Comparision of searches 17 and 18 confirmed that search 19 is a small subset of 14.

cultivar, and to compare them with the GFV and GSR model approaches. Specific inclusion criteria were peer-reviewed literature indexed in the Web of Science (WoS) database (date of search: 18/06/2020 for searches 1-3, 7, 9-19; 18/08/2020 for searches 4, 7-8, 10), published between 1980 and 2020, with all languages and all document types considered. Each search was by "topic"; Table 1 summarises the WoS search queries. It was assumed that this search process covered the most relevant journal-based publications on temperature-based approaches to characterising and understanding differences in grapevine cultivar. Searches 1-3 covered publications on the broad topic, which did not provide information at the cultivar/variety level and were therefore not assessed as being relevant. The 20 most cited articles and the 20 most recent articles from searches 9, 14, and 19 were evaluated for their relevance, and those deemed relevant were evaluated for their temperature-based approach used to understand and characterise cultivar differences.

2. Evaluation of the parameterisations of the top 20 cultivars characterised by the GFV and GSR models

The 20 cultivars with the greatest number of data from Parker *et al.* (2013) and Parker *et al.* (2020) across the three stages (50 % flowering, 50 % véraison for GFV, and the target sugar concentration of 190 g/L for GSR) were evaluated for relative timing of stages, order of classification and size of confidence intervals. The target of 190 g/L was chosen to accommodate both early and late ripening cultivars (as early ripening cultivars often did not have greater target sugar concentrations). F^* values (thermal summations for GFV or GSR models) and confidence intervals (CIs) correspond to those reported in Parker *et al.* (2013) and Parker *et al.* (2020).

3. Validation of the GFV and GSR models with independent databases

The VitAdapt cultivar collection in Bordeaux contains 52 cultivars. Only those for which GFV and GSR parameterisations were available (Parker *et al.*, 2013; Parker *et al.*, 2020) and for which observations were made were included in the analysis. For the GSR model, the 2012-2014 period was omitted due to its use in the GSR model calibration in Parker *et al.* (2020). The data available corresponded to 31 cultivars for 50 % flowering and véraison (period 2012-2017) and for sugar data (period 2015-2017). The average flowering, véraison and sugar concentration dates were obtained from four replicates of 10 vines. Sugar data were collected as follows. At each sampling date, 60 berries were manually sampled from each replicate and each cultivar, and juice was extracted by pressing the berries between two metal blades (Bagmixer 400W - Interscience, France) and then filtered (Lateral BagFilter - Interscience, France) before being centrifuged at 20 °C for 10 minutes at 10,000 rpm. The juice samples (12 mL) were then analysed by Fourier Transform InfraRed Spectroscopy (FTIR), using a WineScan™ analyser according to the method "Must" provided and calibrated by the manufacturer (FOSS, 92000 Nanterre, France). Each sample was analysed twice. The WineScan™ was previously calibrated with an electronic refractometer (Digital Refractometer, Ningbo Gamry Optical Instrument Co., Ltd.) as specified in Destrac *et al.* (2015). Meteorological data were obtained from the INRAE monitoring station located at less than 100 m from the experimental site and at the same altitude. Cultivars in this collection were characterised according to time to flowering and véraison (using the GFV model, individual cultivar F^* values found in Parker *et al.*, 2013) and time to 190 g/L sugar concentrations (using the GSR model, individual cultivar F^* values found in Parker *et al.*, 2020).

Flowering was assessed twice a week at each inflorescence position along a single cane (usually 10 buds) of four 2-caned pruned Sauvignon blanc vines at the Oyster Bay site, Marlborough, New Zealand for the 2004/05 to the 2019/20 growing seasons. Dates of 50 % flowering were determined for each season, and 32 berry samples were obtained weekly from each of the four vines at the site. Véraison was assessed according to berry softness of the weekly 32 berry samples for the seasons from 2005/06 to 2010/2011, and to time to reach the target of 8°Brix from 2011/12 onwards (as determined by the softness–soluble solids correlation described in Parker, 2012). Total soluble solids (TSS) were measured in the juice from the weekly 32 berry samples, and the time to target TSS of 8°Brix (and to an equivalence of 200 g/L target sugar concentration for maturity) was determined. Although 210 g/L is closer to the desired industry target for TSS at harvest (Trought and Bramley, 2011), 200 g/L was chosen as this was obtained in all years of the dataset (not all years reached 210 g/L). Meteorological data were collected from an automated weather station located 0.87 km from the site of observations. Flowering, véraison and time to 200 g/L sugar concentration were predicted using the F^* values for Sauvignon blanc (flowering = 1282, véraison = 2528, GFV model in Parker *et al.*, 2013; time to 200 g/L sugar = 2820, GSR model in Parker *et al.*, 2020) and available temperature data. Yield data were also collected at the site for the same period.

Average flowering and harvest dates for the Champagne region were extracted from the ONERC website (for methodology and results, see: https://www.ecologique-solidaire.gouv.fr/impacts-du-changement-climatique-agriculture-et-foret). The Epernay weather station was selected to model flowering and time to target sugar concentrations in Champagne, because this station is located in the centre of the Champagne production region. Chardonnay flowering dates (F^* = 1217, GFV model in Parker *et al.*, 2013) and dates of attaining a target sugar concentration of 170 g/L were predicted using the available temperature data. This sugar target is the approximate sugar concentration at which Chardonnay is harvested in Champagne (F^* value = 2723, GSR model in Parker *et al.*, 2020). F^* values were chosen for Chardonnay as this variety represents approximately 1/3 of the planted area (the other varieties being Meunier and Pinot noir) and is well distributed over the entire production area. F^* values for flowering and 170 g/L sugar target for Pinot noir are very close to those of Chardonnay, while Meunier is a slightly earlier cultivar (Parker *et al.*, 2013; Parker *et al.*, 2020). The predicted dates were then compared with general flowering and harvest dates from the ONERC website data.

Model efficiency (*EF*, equation 1, Nash and Sutcliffe, 1970), root mean square error (*RMSE*, equation 2), and mean bias error (*MBE*, equation 3) were assessed for the whole dataset of each of the three sites, while *RMSE* and *MBE* were calculated for validation for each cultivar in the VitAdapt collection and for Sauvignon blanc in Marlborough, and Chardonnay in Champagne.

$$EF = 1 - \left(\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \right) \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}} \quad (2)$$

$$MBE = \frac{\sum_{i=1}^{n} S_i - O_i}{n} \quad (3)$$

where O_i is the observed value, S_i is the predicted value, $\bar{O}$ is the mean observed value, and n is the number of observations.

4. Future projections for flowering and time to 170 g/L sugar concentration in Champagne under RCP 4.5 and RCP 8.5 emission scenarios

Yearly dates of 50 % flowering and the time to 170 g/L target sugar concentrations were predicted for the period 2020-2100 from climate model predictions based on the RCP 4.5 and RCP 8.5 emission scenarios. We used the climatic data generated by the ALADIN-Climat v5 Regional Climate Model (CNRM) (12-km resolution) for the CMIP5 experiment downscaled to an 8-km resolution using a quantile–quantile method (http://www.drias-climat.fr/). Daily mean, minimum and maximum temperatures for RCP 4.5 and RCP 8.5 scenarios were used.

RESULTS

1. Review of relevant literature

The web search produced 444 publications containing grape*, temperature* and phenology*, of which 203 also included the terms variety/varieties or cultivar/cultivars (Table 1). Ninety percent of the total number of publications were published after 2008. Only nine publications which addressed the complete topic of temperature, phenology model, and variety/cultivar classification were obtained (Search 19 in Table 1), of which six were considered relevant. By contrast, when the term “classification” was omitted, 88 publications considered grape, cultivar/variety, temperature, phenology and model (Search 14 in Table 1). Out of these 88 publications, 90 % were published after 2008. Overall, there were fewer articles specifically addressing bioclimat* in the search (Searches 3, 11, 15 and 16 in Table 1), and only two publications where bioclimat* (i.e., bioclimatic approaches with a classification) were considered (Search 15 in Table 1). Table 2 summarises the key phenology and bioclimatic approaches found in the 20 most recent and 20 most cited publications for searches 9, 14 and 19. Few key bioclimatic indices were used in these studies. Specific approaches were developed for budburst, notably to take into account chill units (Table 2).

However, four different modelling/temperature-based approaches were tested for flowering and véraison, and likewise four different approaches

TABLE 2. Modelling and temperature-based approaches characterising cultivar differences from relevant literature obtained from the 20 most recent and 20 most cited publications.

Search number[1]	Model/ temperature-based approach	Phenophase/ fixed start date	Stage(s)	Number of cultivars characterised	Publication
9, 14,19	BRIN[2]	Fixed	Budburst	10	García de Cortázar-Atauri *et al.* (2009)
9, 14	Dynamic model	Phenophase	Budburst	23	Ferguson *et al.* (2014)
9	Photoperiod + Chill and heat requirements		Budburst	2	Camargo-Alvarez *et al.* (2020)
9	Uniforc[3] (non-linear forcing)	Phenophase	Budburst	1	Prats-Llinas *et al.* (2020)
9	VineLOGIC	Unknown Phenophase	Budburst Harvest	2	Webb *et al.* (2007)
9	Average temperatures at set time periods	Fixed	Budburst Flowering Véraison Harvest	18	Tomasi *et al.* (2011)
9, 19	Statistical models of climate over fixed periods	Fixed	Budburst Flowering Véraison	16	Fraga *et al.* (2016)
9, 14	GFV[4] (form of GDD)[5]	Fixed	Flowering Véraison	11 11	Parker *et al.* (2011)
9, 14, 19	GFV[4] (form of GDD)[5]	Fixed	Flowering Véraison	95 104	Parker *et al.* (2013)
9	GFV[4] GSR[6]		Flowering Véraison Maturity	1	Ramos and Martinez de Toda (2020)
9	Single triangulation	Phenophase	Flowering Véraison Maturity (sugar/soluble solids concentration)	1	Prats-Llinas *et al.* (2020)
9	GDD[5] (Fixed period of time Sept-Oct)	Fixed	Maturity (target sugar concentration)	23	Cameron *et al.* (2020)
9,19	GSR[6] (form of GDD[5])	Fixed	Maturity (target sugar concentration)	65	Parker *et al.* (2020)
9, 14	Huglin Index (Huglin, 1978)	Fixed Phenophase Phenophase	Budburst Flowering Véraison	14	Duchêne *et al.* (2010)
9, 14	GST[7]	Fixed	Maturity (sugar/soluble solids concentration)	7	Webb *et al.* (2012)
14	Daily average temperature	Fixed	Onset of maturity (assessed by sugar/soluble solids concentration) Maturity (sugar/soluble solids concentration)	3	Sadras and Petrie (2011)
14	Range of climate variables (80 predictors tested)	Fixed	Budburst Flowering Véraison	7	Urhausen *et al.* (2011)

[1]Search 9: TS = (grape* AND cultivar* AND temperature* AND phenolog*) or TS = (grape* AND variet* AND temperature* AND phenolog*); Search 14: TS = (grape* AND variet* AND temperature* AND phenolog* AND model*) or TS = (grape* AND cultivar* AND temperature* AND phenolog* AND model*); Search 19: TS = (grape* AND temperature* AND phenolog* AND model* AND classification AND variet*) OR TS = (grape* AND temperature* AND phenolog* AND model* AND classification AND cultivar*).
[2]The BRIN model combines the Bidabe model for chill units (Bidabe, 1965a, b) and the Richardson model for forcing/heat units (Richardson *et al.*, 1974).
[3]Uniforc in Chuine (2000).
[4]GFV: Grapevine Flowering Véraison.
[5]GDD: Growing Degree Days.
[6]GSR: Grapevine Sugar Ripeness.
[7]GST: Growing Season Temperature.

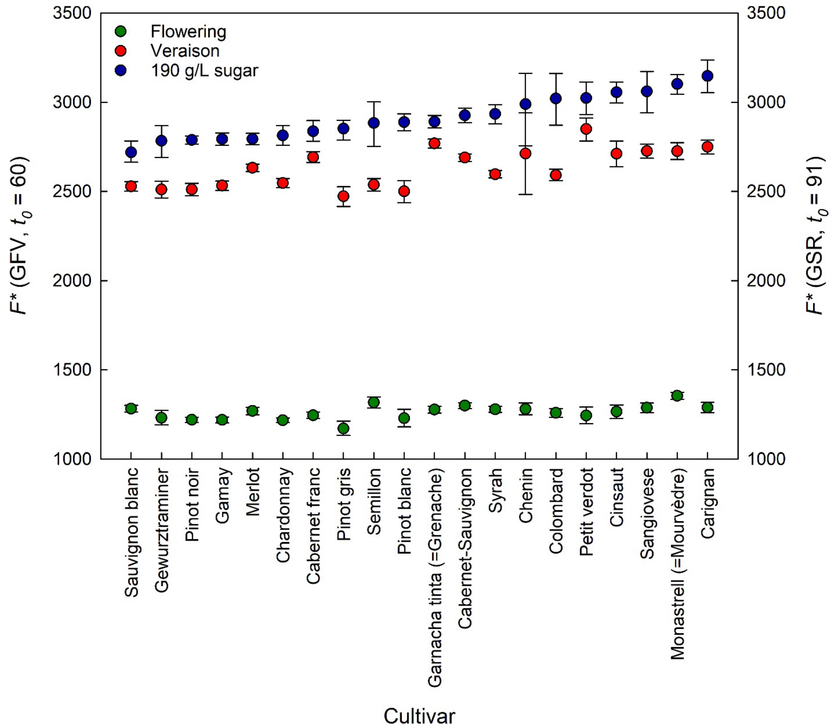

FIGURE 1. Top 20 cultivars common to the historical databases for the Grapevine Flowering Véraison and Grapevine Sugar Ripeness models.

for measuring maturity (Table 2). The GFV and GSR models have been used to characterise the greatest number of cultivars to date (Table 2).

2. Comparison of classification orders of cultivars for the GFV and GSR models based on original datasets

In the original datasets of Parker *et al.* (2013) and Parker *et al.* (2020), eight cultivars (Merlot, Pinot noir, Grenache, Cabernet-Sauvignon, Gamay, Syrah, Chardonnay, Cabernet franc) were in the top 10 cultivars in terms of number of observations for the stages of flowering, véraison and time to 190 g/L sugar concentration.

For the top 20 cultivars, when ranked in terms of the smallest thermal time (F^*) to the largest thermal time to reach 190 g/L of sugar by the GSR model, the order was different to that of earliest to latest flowering, and likewise to that of earliest to latest véraison. In general, early véraison cultivars reached the 190 g/L target sugar concentration early, and late véraison cultivars reached this target late. However, the mid-range cultivars for the time to 190 g/L sugar concentration experienced variation in the order of timing when comparing véraison with time to 190 g/L sugar; for example, Chardonnay véraison was earlier than that of Merlot, but the time to 190 g/L sugar concentration was very similar for both, and Grenache, Cabernet-Sauvignon and Syrah displayed vastly different timings for véraison, but reached 190 g/L sugar at a similar time. When comparing the order of time to 190 g/L sugar concentration to the flowering and véraison order, nine cultivars changed their order by greater than five places for two or three of the phenological stages (Table 3). All confidence intervals were less than 150 degree days for flowering and veraison for these cultivars, except véraison for Chenin, for which the CI was > 350 degree days (Figure 1), where five out of the six years had differences in observations and predictions of more than six days, and the EF was -1.56. Fourteen cultivars had CIs of < 150 degree days (excluding Semillon, Chenin, Colombard, Petit verdot, Sangiovese and Carignan) for the time to target sugar concentration of 190 g/L, and only Chenin exceeded 300 degree days (Figure 1).

3. Validation of the GFV and GSR models using independent databases

3.1. VitAdapt cultivar collection, Bordeaux, France

EF values for all three stages indicated that the models performed better than when just using the average of the dates alone - with values of EF > 0.5 being considered to indicate sufficient model quality - and the average error of prediction

TABLE 3. Cultivars with order changes greater than five places within the top 20 classification for the stages flowering (determined by the Grapevine Flowering Véraison model, GFV), véraison (GFV model), or time to 190 g/L sugar (determined by the Grapevine Sugar Ripeness model).

Cultivar	Flowering classification position	Véraison classification position	190 g/L sugar classification position
Merlot	*11*	*11*	5
Chardonnay	2	*8*	*6*
Pinot gris	*1*	*1*	8
Semillon	19	*7*	*9*
Grenache	*12*	19	*11*
Cabernet-Sauvignon	18	*12*	*12*
Colombard	*9*	*9*	15
Petit verdot	7	*20*	*16*
Cinsaut	10	*14*	*17*

Numbers in *italics* indicate similar positions for two out of the three stages for each cultivar.

TABLE 4. Validation of Grapevine Flowering Véraison (GFV) and Grapevine Sugar Ripeness (GSR) models for three different data sources.

Site		Multiple cultivars[1], VitAdapt site, Bordeaux, France (2012-2017 GFV, 2015-2017 GSR)	Sauvignon blanc, Oyster Bay, Marlborough, New Zealand (2004-2020)	Epernay, Champagne, France (1961-2019) [3]
EF	50 % Flowering	0.55	-1.04	0.48
	50 % Véraison	0.71	0.30	-
	Target sugar concentration[2]	0.48	-0.10	0.63
RMSE	50 % Flowering	4.70	6.67	6.83
	50 % Véraison	5.07	4.67	-
	Target sugar concentration[2]	6.52	9.67	7.12
MBE	50 % Flowering	-1.21	-5.50	-4.05
	50 % Véraison	-1.66	1.80	-
	Target sugar concentration[2]	3.18	-2.40	-3.17
n	50 % Flowering	6 (173 observations)	16 (2004/05 to 2019/20)	58
	50 % Véraison	6 (181 observations)	15 (2005/06 to 2019/20)	-
	Target sugar concentration[2]	3 (89 observations)	16 (2004/05 to 2019/20)	58

EF = model efficiency, *RMSE* = root mean square error, *MBE* = mean bias error; n = number of years where observations were recorded and predictions generated.
[1] 31 cultivars were analysed.
[2] 190 g/L for VitAdapt site, Bordeaux, France; 200 g/L for Oyster Bay, Marlborough, New Zealand; 170 g/L for Epernay, Champagne, France, using the cultivar Chardonnay.
[3] Flowering dates were the average of the region; the GSR model predicted 170 g/L sugar, whereas the observed data was in the form of harvest dates; no véraison data were available for this site.

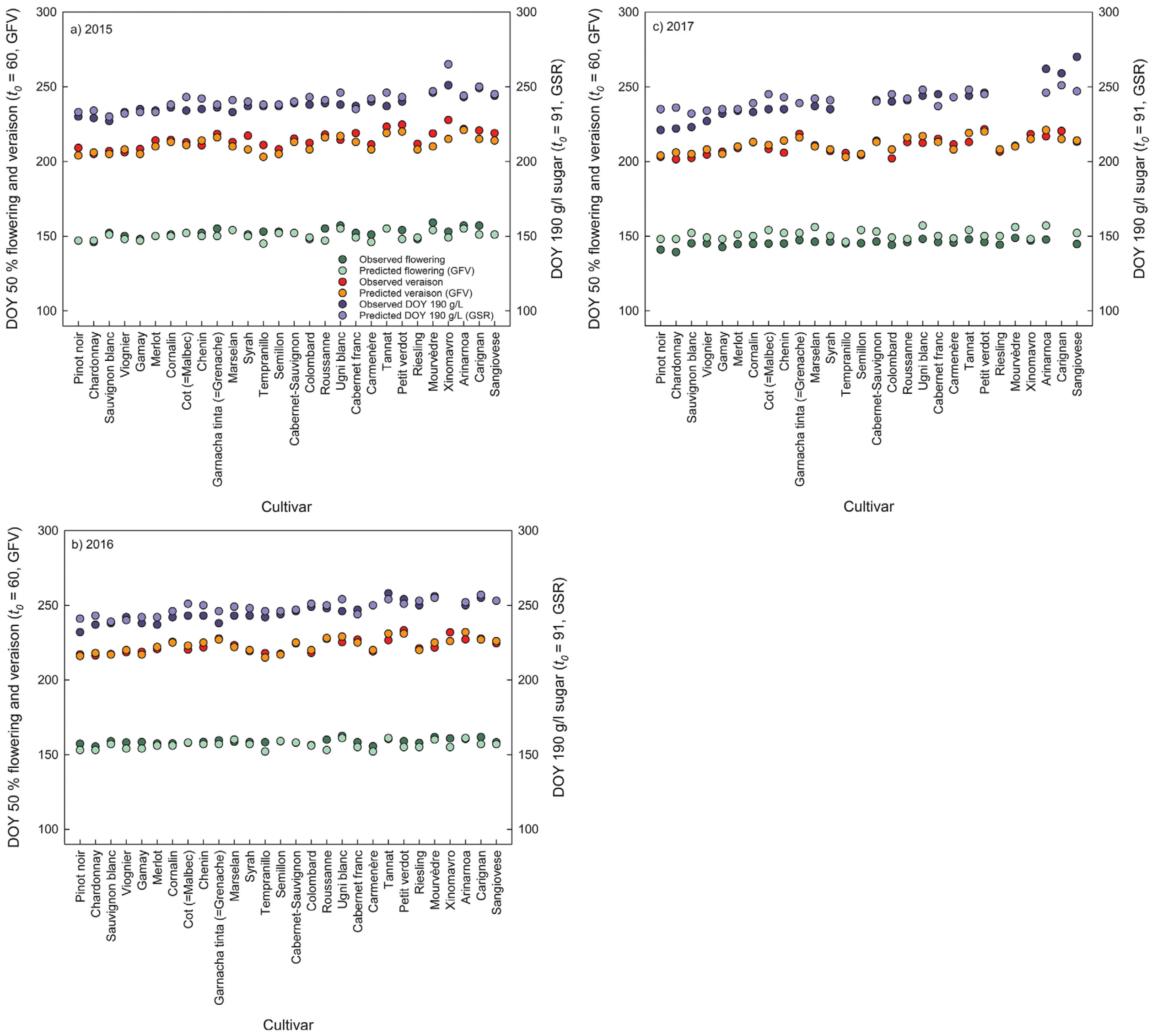

FIGURE 2. Grapevine Flowering Véraison (GFV) and Grapevine Sugar Ripeness (GSR) model classifications for cultivars in the VitAdapt collection for a) 2015, b) 2016 and c) 2017.
Only cultivars for which all three stages were modelled in at least one year are shown.

(*RMSE*) was less than a week for all three stages (Table 4). *MBE*s indicated that 50 % flowering and véraison overall were predicted earlier than the observations, and the reverse was true for time to 190 g/L sugar concentration (Table 4).

The assessment of model performance for individual cultivars indicated that 94 %, 87 % and 70 % of the cultivars had average errors of prediction of a week or less (*RMSE*) for flowering, véraison and time to 190 g/L sugar respectively, with most cultivars with less than 10 days for all three stages (100 % for flowering and véraison, 94 % for the time to 190 g/L sugar concentration) (Table 5). *MBE* values for individual varieties were in the ranges -6.58 to 2.98 (flowering), 7.77 to 5.43 (véraison) and -7.33 to 9.67 (time to 190 g/L sugar concentration) (Table 5). Of these values, 61 % of the cultivar predictions for flowering were earlier than the observations. For 76 % of the cultivars, véraison was predicted before the observation, but only 19 % predictions for the time to 190 g/L target sugar concentration were before the observations (Table 5). For four out of the six seasons analysed, the difference between predicted and observed values varied in a non-systematic way per cultivar for flowering.

The exceptions were for flowering in 2013, when predictions were earlier than observations for all cultivars, and in 2017, when predictions were later than observations. For véraison there were no systematic differences in yearly predictions and observations, except in 2013 when predictions

TABLE 5. Performance of Grapevine Flowering Véraison (GFV) and Grapevine Sugar Ripeness (GSR) models for individual cultivars in the VitAdapt collection.

Cultivar	Flowering			Véraison			190 g/L sugar		
	RMSE	MBE	n	RMSE	MBE	n	RMSE	MBE	n
Alvarinho							10.66	9.67	3
Arinarnoa	4.45	0.17	6	4.62	0.26	6	9.33	-4.33	3
Cabernet franc	4.96	-3.12	6	5.96	-5.22	6	5.07	-4.33	3
Cabernet-Sauvignon	3.62	-0.35	6	3.52	-2.40	6	1.00	0.33	3
Carignan	6.33	-5.67	5	7.09	-5.31	6	4.80	-1.67	3
Carmenère	4.89	-3.74	6	5.19	-3.53	6	1.15	0.67	3
Chardonnay	3.98	0.93	6	4.15	0.68	6	9.26	8.33	3
Chasselas	4.69	2.98	6	6.09	5.43	6			
Chenin	3.76	-0.54	6	6.09	3.80	6	7.35	7.33	3
Colombard	2.95	1.85	3	3.82	1.01	4	4.24	4.00	3
Cornalin	2.96	-0.50	6	1.39	-1.04	5	4.32	4.00	3
Cot (= Malbec)	4.23	0.54	6	3.65	-0.72	6	9.04	9.00	3
Gamay	3.73	-1.50	6	5.34	-3.76	6	3.11	1.67	3
Garnacha tinta (= Grenache)	5.50	-3.35	6	4.73	-2.72	6	4.76	3.33	3
Hibernal							8.64	8.00	3
Liliorila							5.20	4.33	3
Marselan	4.48	1.62	6	4.54	-3.04	6	6.45	6.33	3
Merlot	3.43	-0.34	6	3.81	-2.00	6	3.00	1.67	3
Mourvèdre	6.26	-3.03	6	4.83	-2.38	6	1.00	0.00	2
Muscadelle	4.78	1.60	6	4.78	-2.86	6			
Petit verdot	6.26	-4.40	6	6.45	-4.76	6	2.52	-0.33	3
Petite Arvine	3.53	-0.62	6	4.16	-1.64	6			3
Pinot noir	4.19	-1.03	6	5.05	-1.92	6	9.76	8.67	
Riesling	3.00	0.61	6	4.35	-3.00	6	3.00	3.00	1
Roussanne	7.91	-6.54	6	3.32	-1.37	6	1.73	1.67	3
Sangiovese	3.52	0.06	6	4.05	-2.41	6	13.29	-7.33	3
Saperavi							7.14	5.00	3
Sauvignon blanc	3.47	-0.57	6	3.64	-1.50	6	5.51	4.33	3
Semillon	4.16	0.47	6	3.75	-2.12	6	1.58	1.50	2
Syrah	2.38	0.45	3	5.32	-3.29	5	4.83	4.67	3
Tannat	3.61	2.42	3	8.00	4.90	6	6.14	3.00	3
Tempranillo	7.62	-6.56	6	7.23	-5.65	6	2.92	2.50	2
Touriga Nacional							6.93	6.67	3
Ugni blanc	4.86	-1.09	6	3.48	2.31	6			
Viognier	4.27	-2.69	6	3.44	0.28	6	4.24	1.33	3
Xinomavro	4.25	-3.06	3	8.49	-7.77	5			

RMSE = root mean square error, *MBE* = mean bias error, n = number of observations. Positive *MBE* values mean predictions are earlier than observations.

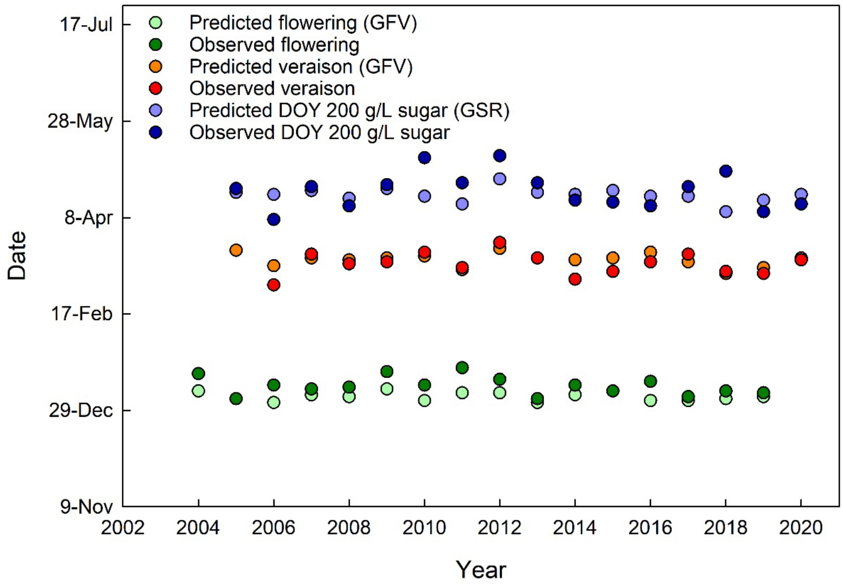

FIGURE 3. Validation of the Grapevine Flowering Véraison (GFV) model time to flowering and véraison and the Grapevine Sugar Ripeness (GSR) model for the time to 200 g/L sugar concentration for Sauvignon blanc at Oyster Bay, Marlborough, New Zealand.
Note that within a season flowering occurs in the calendar year preceding that of véraison or harvest.

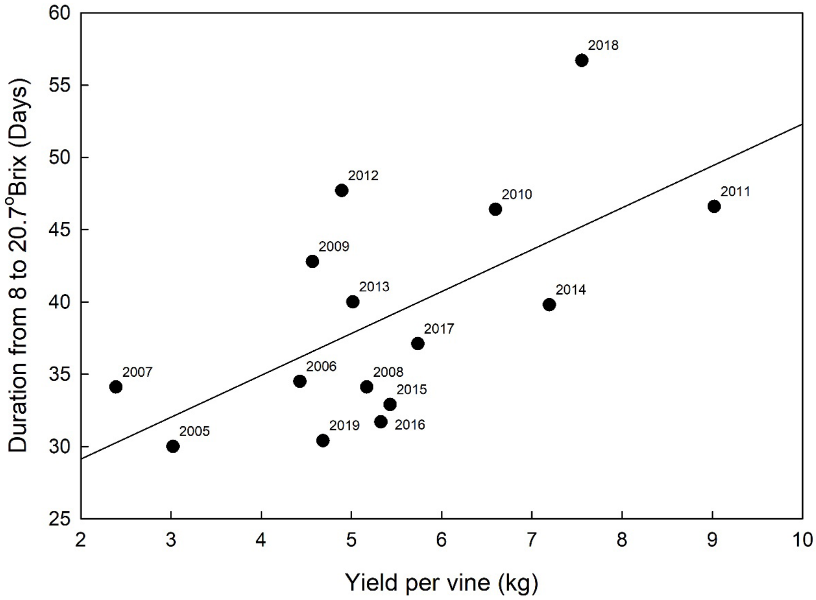

FIGURE 4. Duration from 8 to 20.7°Brix for Sauvignon blanc as a function of yield per vine at Oyster Bay, Marlborough, New Zealand.
$R^2 = 0.40$.

were earlier than observations. In 2015, however, predictions were later than observations for the time to 190 g/L sugar. For the three years when there were common data for all cultivars and stages (2015-2017), the difference between observed and predicted values for each stage was, on average, as follows: flowering: 2 (2015), 2.5 (2016), and 5.9 days (2017) with a range of 0-10 days (for all 3 years); véraison: 4.1 (2015), 1.9 (2016), and 2.7 days (2017) with a range of 0-13 days (for all 3 years); time to 190 g/L sugar: 3.6 (2015), 3.7 (2016) and 6.7 days (2017) with a range of 0-23 days (for all 3 years) (Figure 2).

3.2. Sauvignon blanc at Oyster Bay, Marlborough, New Zealand

The error of prediction (*RMSE*) was less than one week for flowering and véraison and 9.67 days for time to 200 g/L sugar concentrations for Sauvignon blanc at the Oyster Bay site in

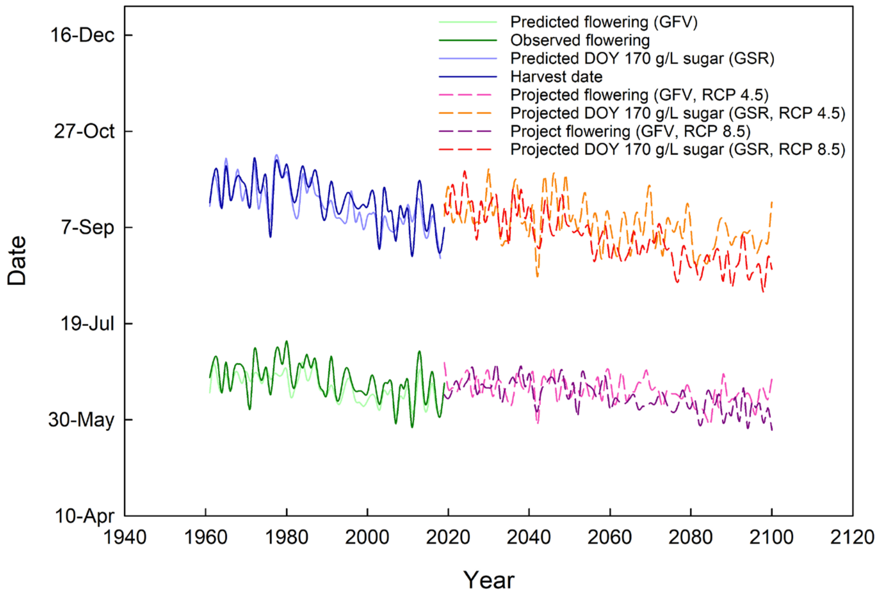

FIGURE 5. Validation of flowering date predicted by the Grapevine Flowering Véraison (GFV) model and time to 170 g/L sugar concentration predicted by the Grapevine Sugar Ripeness (GSR) model for Chardonnay in Champagne, with future projections of flowering and time to 170 g/L sugar concentration for RCP 4.5 and RCP 8.5.

Marlborough (Table 4). Flowering and target sugar concentrations were in general predicted earlier than observed; conversely, véraison was predicted later than observed (*MBE* values, Table 4). The *EF* for véraison was 0.3, while the *EF* values for flowering and the time to 200 g/L sugar concentrations were negative (-1.04 and -0.10), indicating that the average value of the observed time to 200 g/L was a better predictor than the model for the dataset used (2004/05 season to 2019/20, Table 4). There were large differences in predicted and observed values for both stages in 2005/06, with smaller differences between observations, which contributed to the low *EF* (Figure 3). Except for 2005/06, all the seasons with large differences between predicted and observed values had higher yields, which was associated with slower ripening rates (Table 4 and Figure 4).

3.3. General flowering and harvest dates for Champagne, France

When comparing the general flowering and harvest dates with those simulated by the GFV and GSR models for Chardonnay in Champagne, France, the error of prediction (*RMSE*) was less than, or equal to, one week for flowering and the time to 170 g/L sugar concentration (Table 4). In the 58 years for which both predicted and observed values were evaluated, more than 70 % of the years had a difference of less than one week between the observed and predicted dates for both flowering and time to 170 g/L sugar concentration (Figure 5), resulting in model efficiencies of 0.48 and 0.63 respectively (Table 4 and Figure 5). Overall, predictions were earlier than observations for both stages (*MBE* values in Table 4 and Figure 5).

4. Future projections for flowering dates and time to 170 g/L sugar concentration in Champagne under the RCP 4.5 and RCP 8.5 emission scenarios

For the period 2020-2100, flowering dates were projected to advance at a rate of almost 0.1 days/year for RCP 4.5 (i.e., one day per decade, $y = -0.0981x + 367.13$) and 0.22 days/year for RCP 8.5 (i.e., two days per decade, $y = -0.2209x + 617.41$) (Figure 5). The time to reach the target sugar concentration of 170 g/L was predicted to advance at a faster rate of 0.2 days/year (i.e., two days per decade, $y = -0.2142x + 692.7$) than flowering dates for the same period for RCP 4.5. Likewise, the projected time to 170 g/L under RCP 8.5 advanced at faster rate of 0.49 days/year (i.e., five days per decade, $y = -0.4901x + 1253.8$) than the RCP 4.5 scenario projections (Figure 5).

DISCUSSION

The highest wine quality is obtained when grapes ripen neither too early, nor too late in the season (van Leeuwen and Seguin, 2006). Excessively early ripening results in grapes with extreme sugar levels (leading to excessive alcohol in the resulting wines) and which are too low in organic acids (leading to wines lacking freshness). Ripening which is too delayed relative to the desired ripening window for a given region, variety or wine style, may result in unripe grapes and acidic wines marked by green flavours (van Leeuwen and Seguin, 2006; Pons *et al.*, 2017). Grapevine cultivars (*Vitis vinifera* L.) have a wide range of heat requirements for reaching specific phenological stages or sugar target levels. The GFV and GSR models can be used to predict if a given cultivar will reach subsequent phenological stages and sugar ripeness within the ideal timeframe under current and future climatic conditions (Parker *et al.*, 2013; Parker *et al.*, 2020). Furthermore, because the GSR model uses an objective measure of the time to reach target sugar concentrations, it can also accommodate different wine styles for which sugar concentrations are of importance (e.g., sparkling wines and low alcohol wine styles). The extensive evaluation of the GFV and GSR models in this research has demonstrated that models are useful tools to assess whether a given cultivar is adapted to a specific site, and if it will be suitable in future climatic conditions.

1. Evaluation of temperature-based approaches to characterise and understand cultivar differences for the grapevine

Even though only a few cultivarss were often considered, the extensive literature review highlighted a range of temperature-based approaches to understanding cultivar differences. However, several studies providing important approaches and knowledge regarding the application of phenology modelling for characterising small numbers of cultivars were not highlighted in the review (e.g., Moncur *et al.*, 1989; Molitor *et al.*, 2014; Molitor *et al.*, 2020; Morales-Castilla *et al.*, 2020). Apart from the approaches using the GFV and GSR models, many statistical assessments of cultivar differences in the top 20 cited or recent publications have been based on coarse climatic timeframes (e.g., often using monthly data), which cannot be directly related to the date of appearance of the key phenological stages (Sadras and Petrie 2011; Tomasi *et al.*, 2011; Webb *et al.*, 2012; Fraga *et al.*, 2016). Such approaches are therefore unable to directly represent plant response to temperature.

Of the 20 most recent and cited references, there were models which used fixed start dates, and others that used the previous phenological stage from which to predict the phenological stage of interest (the phenophase approach). A few studies have implemented phenophase approaches for different cultivars without a classification objective (García de Cortázar-Atauri *et al.*, 2010; Molitor *et al.*, 2014; Molitor *et al.*, 2020; Morales-Castilla *et al.*, 2020). This enables specific cultivar models to be developed and predictions to be based on previous phenological stages rather than on fixed start dates, the limitation of the latter being that start dates are not always synchronous with plant development. However, it was not possible to use a phenophase approach with the GFV and GSR models, as it would not have enabled a classification to be generated (as the start time would have differed for each cultivar). Furthermore, in the case of cultivars with little data, using GFV and GSR models that have been successfully developed for application to a wide range of cultivars, sites and years, would enable the characterisation of less represented cultivars, for which it would be difficult to create phenophase models.

Some previous well-known classifications were not detected during the comprehensive literature search, which is likely due to the absence of modelling approaches, or to the source of the classification not being within the search configuration (e.g., dates or resources in the database). Key omitted classifications that have previously contributed to our understanding of cultivar differences in phenology include: the classification of 26 cultivars into nine groups based on the Huglin index for the time to 200 g/L sugar concentration by Huglin (1978); the classification of 114 cultivars based on the timing of budbreak, bloom and onset of véraison at the UC Davis site (McIntyre *et al.*, 1982); the classification of budburst and leaf appearance for 10 cultivars by Moncur using a temperature-based experimental model development approach (Moncur *et al.*, 1989); Boursiquot *et al.* (1995) classification of 2168 cultivars for maturity via tasting of berries in the field; Jones's (2006) suitability index which grouped cultivars according to maturity relative to average growing season temperatures (Northern Hemisphere Apr-Oct; Southern Hemisphere Oct-Apr); and Gladstones (2011) classification of 138 cultivars into nine maturity groupings based on Biological Effective Degree Days (heat accumulation defined by temperature thresholds of 10 and 19 °C adjusted for latitude). While many of these maturity groupings are useful, some do not incorporate temperature-based approaches and often do not specifically characterise the individual cultivar thermal summations as characterised for the GFV and GSR models, but rather group the cultivars. Therefore, compared to the other classifications in the literature, the GFV and GSR classifications (Parker *et al*., 2013; Parker *et al.*, 2020) go beyond broad groupings of cultivars. These classifications currently provide the most detailed individual cultivar parameterisations, which is a useful resource for understanding cultivar differences for new cultivars in a region or site, especially where few data or information is available.

The search term 'bioclimat*' may not have picked up all articles in this research area, potentially due to the use of the specific names of bioclimate indices rather than the terms 'bioclimate/bioclimatic'. The search excluded studies that addressed zoning/general climate suitability, which do not take into account the plant response to temperature. However, these approaches, which were under-represented in the literature search results, still provide a useful and valuable methodology for investigating the suitability of areas for grape production, particularly in the context of climate change (e.g., recent work Santos *et al.*, 2019). Combining bioclimatic indices and phenological models could provide a more comprehensive assessment of the suitability of sites and cultivars in future studies.

2. Application of the GFV and GSR models for assessing new sites and cultivars

The application of the GFV and GSR models to three new situations – the VitAdapt cultivar collection, Chardonnay data from Champagne, and Sauvignon blanc data from Marlborough – highlighted that these models are easy-to-use and sufficiently accurate from a commercial perspective when applied to new sites. The VitAdapt results indicated that the parameterisations established in Parker *et al.* (2013) and Parker *et al.* (2020) performed well, with overall errors of prediction (*RMSE*s) of generally less than one week for flowering and véraison, and less than 10 days for time to 190 g/L sugar concentration. There were few seasonal trends in predictions, except for a bias in the 2013 season with predictions earlier than observations, which may be partially attributed to delayed budburst (i.e., delayed start of phenological development relative to the start date of the GFV calculation). Model performances were poorer in 2013, because of unfavourable meteorological conditions during flowering inducing fertilisation problems, as well as the cool and rainy weather during grape ripening causing some issues with *Botrytis*.

The analysis of the VitAdapt cultivar collection also highlighted specific cultivars for which the models' performance was more variable. Carmenère, Roussanne, Tempranillo and Xinomavro generally had big differences between predicted and observed values for flowering and véraison (> 5 days). The classifications in Parker *et al.* (2013) showed that confidence intervals (CI) were large (> 350) for Roussanne and Xinomavro for flowering and véraison, while CI values were large for Tempranillo and Roussanne (> 350) for the 190 g/L sugar concentration in Parker *et al.* (2020). However, these three cultivars had few data points in the original classifications, and the detailed analysis of the 2015-2017 period highlighted that the overall (all cultivar) average yearly differences between predictions and observations were low (often as low as 2-3 days). Given that the overall model performance was satisfactory across all cultivars, this indicates that the *F** characterisations for flowering, véraison and time to reach target sugar concentration for both GFV and GSR models could be improved for these specific cultivars in the future.

Errors of prediction were generally larger for the time to 190 g/L sugar than flowering and véraison for the whole dataset, and for individual cultivar data from the VitAdapt site. This can be attributed to fewer years being evaluated (only 2015-2017 for 190 g/L sugar), and also to the fact that other factors, such as water deficit (van Leeuwen *et al.*, 2009), leaf area to fruit weight ratios (Parker *et al.*, 2014a; Parker *et al.*, 2014c; Parker *et al.*, 2015a), and clonal differences (van Leeuwen *et al.*, 2013), may have contributed to the variation in ripening rates, and therefore to the time to reach target sugar concentrations. The GSR analysis for Sauvignon blanc in Marlborough highlights this point with increased yields being generally associated with longer ripening periods. The GFV and GSR models proved highly accurate when used on long term past climate data (the Champagne simulation), which provides the opportunity to simulate phenology of existing cultivars in given regions based on meteorological data, with the proviso that the original cultivar calibrations (Parker *et al.*, 2013; Parker *et al.*, 2020) indicate high *EF*s and low RMSEs. This is a useful approach to characterising trends over time when observations may not always be available.

The application to Sauvignon blanc in Marlborough indicated good performance for all stages as assessed by RMSE, but yield and climate drivers (cool seasons, high rainfall and low sunshine hours) may have led to reduced model performance as assessed by *EF*. This was notably the case for 2017/18, when predictions were substantially earlier than observations for the time to reach 200g/L sugar concentration, and rainfall was 236 % of the long-term average for the period Jan-March, a season which also had the lowest total solar energy (89.5 % of the long-term average, LTA). The 2009/10 and 2010/11 seasons were also cooler with delayed phenology relative to the LTAs, and high yields. 2005/06 observations were earlier than predictions for véraison and harvest, and this was the earliest year on record for phenological stages (budburst six days earlier than the LTA, flowering six days earlier than the LTA, and time to véraison 13 days earlier than the LTA). Therefore, while the application of both models led to small errors in predictions, errors may be larger for certain years; it is thus also important to investigate where and why these occur, in particular in later phenological stages, in order to define potential limits of model application in given locations.

The analysis of the ranking of classifications of the most represented cultivars in the historical database indicated that, while cultivars generally stay in broad groups of 'early', 'medium' and 'late' for various stages, the specific sequence of cultivars may change over the various stages of phenology. For example, Grenache, Cabernet-Sauvignon and Syrah displayed vastly different timings for véraison using the historic dataset from Parker *et al.* (2013), but reached 190 g/L sugar at a similar time based on the historical dataset from Parker *et al.* (2020). This also confirms recent research by Molitor *et al.* (2020), who found that for the seven cultivars tested in their study, the order of cultivars varied depending on the phenological stage. Within a site, as in the case of the VitAdapt collection, most cultivars remained within five places within the classification rankings across the various stages (2015-2017). Notably though, the order for véraison did not match that of the time to target sugar concentration for either the historical dataset or the VitAdapt collection. Potential reasons for this are: véraison is observed subjectively in the field, whereas the sugar concentrations are measured on berries in the laboratory so that scales of measurement and the nature of the measurements differ; maturity is associated with cultivar dependent rates of soluble solids accumulation as a result of changes in water dynamics in berries (Sadras *et al.*, 2008); and, as mentioned earlier, other environmental and management factors may have slightly different consequences for ripening rates for different cultivars.

3. Application of the GFV and GSR models for cultivar choice in the context of climate change

Coupling GFV and GSR models with future climate change projections can be useful to determine when cultivars that are traditionally grown in a given area will no longer be adaptable in the future. The results for Champagne under RCP 4.5 indicate that while flowering and ripening may potentially advance by up to 5 and 10 days respectively by the end of the century, this would not necessarily mean that Chardonnay would no longer be suitable for the region. However, ripening projections under RCP 8.5 indicate that Chardonnay may no longer be suitable. van Leeuwen *et al.* (2019) stated that Merlot and Sauvignon blanc would no longer be suitable in Bordeaux (based on defining a desired ripening period) by 2050, based on a + 1°C temperature increase. Therefore, it is important to apply phenological models in combination with climate projections at specific locations and to specific cultivars, as not all locations or cultivars will have equivalent outcomes. The coupling of different climate models and RCP scenarios may result in different outcomes, although recent research have shown that trends remain more or less constant among climate models for the same RCP scenarios (Marjou and García de Cortázar-Atauri, 2019; Morales-Castilla *et al.*, 2020). However, as climate models and RCP projections continue to evolve, we may need to consider different models and projection pathways in the future, or adjust our prior evaluations. Furthermore, when considering adaptation for potential wine styles, such as Champagne, other key factors, such as the impact of elevated temperatures on acidity, need to be taken into account. Understanding the effect of changes in more than just sugar concentrations on wine style and typicity will be crucial for determining cultivar suitability in the future; for example, Sadras and Moran (2012) demonstrated that anthocyanin and sugar evolution during ripening became asynchronous under elevated temperatures, and Sadras *et al.* (2013) demonstrated that grapes exposed to elevated temperatures had variable changes in pH and acidity depending on cultivars, as well as cultivar-specific changes in aroma, flavour and mouthfeel of the resulting wines.

The GFV and GSR models are simple in application (linear in form, with a base temperature of 0 °C). However, extremely elevated temperatures in the context of climate change could have a negative impact on plant development, causing decreased rates of development, which can be captured in non-linear models such as the Wang-Engel model (Wang and Engel, 1998). This latter model was tested during the GSR model development, and with other non-linear models (UniFORC) (Chuine, 2000) during the GFV and GSR model development, and it was found that most non-linear models did not improve predictions in the context of those studies. The exception was that the sigmoid model performed just as well as the GSR, and hence a classification based on this model is also presented in Parker *et al.* (2020). Such non-linear models have been successfully applied elsewhere for predicting grapevine phenology (García de Cortázar-Atauri *et al.*, 2010; Cuccia *et al.*, 2014; Molitor *et al.*, 2014; Molitor *et al.*, 2020; Morales-Castilla *et al.*, 2020; Prats-Llinas *et al.*, 2020). Furthermore, as the GFV and GSR models have fixed start dates, if budburst advances substantially in the future, this may change projections, which is negated if using a previous phenological stage for a start date. Only Cuccia *et al.* (2014) have compared a non-linear model (Wang-Engel) with the linear GFV model in the context of climate change, finding few differences between the two models when tested for +5 °C for Pinot noir véraison in Burgundy. However, when considering future projections of Pinot noir in other regions, they demonstrated there were differences in the predicted time of véraison of Pinot noir provided by GFV and the Wang-Engel model under +5° conditions in the Cagliari and Seville regions, but not in Dijon and Carcassonne. This indicates that under warmer conditions, such as those projected for Cagliari and Seville, it may become important to consider temperature caps or non-linear models that integrate negative impacts of temperature on phenology. However, extreme temperatures that require non-linear modelling approaches may not arise in all current growing regions (e.g., the cooler area of Dijon). Therefore, the type of phenological model suitable for future climate change studies warrants further investigation when considering the specific environmental conditions of a site or region under future climate conditions, and model complexity and fit should always be considered in model choice.

Finally, as phenology can be influenced by environmental events, as well as temperature and management methods, it is important to consider the impacts of current local adaptation initiatives on long term observations. If producers are already manipulating vines during the growing season in attempts to mitigate advances in phenology, then observations from commercial data may be confounded by these adaptation practices. This highlights the importance of continuing phenological observations and records at research sites such as the VitAdapt site, as well as controlling management for research blocks established at commercial sites. However, it will be important to capture changes in cultural practices in the future, as growers take action to adapt to climate change using a range of measures, if we are to further our understanding of the effects of grower adaptation practices, including cultivar change.

4. Future perspectives

Key areas already highlighted for future research include: partnering bioclimate and cultivar phenology for suitability studies in the context of climate change; integrating the influence of other environmental and management practice moderations on phenological responses into current and future cultivar modelling; more in-depth modelling of other berry compositional parameters to evaluate cultivar suitability; and further investigation of the temperature conditions under which capped/non-linear models need to be applied. In addition to these points, downscaling the development or application of existing phenological models is of great interest for adaptation to climate change. de Rességuier *et al.* (2020) demonstrated that using the GFV model they were able to characterise and map sub-regional differences in the timing of flowering and véraison for Merlot within St Emilion (19 233 ha). Verdugo-Vásquez *et al.* (2019) also demonstrated that high resolution information of phenology variability is obtainable and can be modelled using phenological modelling approaches such as GFV. At the VitAdapt site used in this study, it will be possible to investigate in more detail within-site variability and associated predictions of replicates and vines within the block. An issue raised in our study is that some cultivars in the original classifications in Parker *et al.* (2013) and Parker *et al.* (2020) had few observations. While the original classifications present preliminary characterisations of thermal time in relation to the key phenological events, there is an opportunity to improve the F^* characterisation for cultivars with low data representation, as more data become available. This will potentially confirm current positions in classifications, or lead to some amendments. While the classifications in Parker *et al.* (2013) and Parker *et al.* (2020) and Section 4.1 cover a wide range of cultivars, many of the estimated 1100 different cultivars planted today (Wolkovich *et al.*, 2017) have not been characterised by GFV, GSR or any other phenological model. This represents a vast and interesting opportunity to investigate more cultivar choices as an adaptation strategy in response to future climate change.

CONCLUSIONS

The GFV and GSR models are highly accurate and easy-to-use temperature-based phenological models for predicting flowering, véraison and time to reach target sugar concentrations for a wide range of cultivars. They can be applied for the characterisation of new cultivars, or for the assessment of cultivar performance in current or future areas. By combining these models with climate change projections, it is possible to evaluate whether current cultivars within a growing area are suited to future adaptation, or whether cultivar change is required. By continuing to characterise new cultivars, or by improving the characterisation of cultivars with fewer data points in the original classifications, an even more extensive classification of the timing of phenology and ripeness of different cultivars can continue to be developed. This will enable growers and researchers to compare the phenology of cultivars in a region today and to adapt to climate change via appropriate cultivar choice.

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