THE TEMPERATURE-BASED GRAPEVINE SUGAR RIPENESS (GSR) MODEL FOR ADAPTING A WIDE RANGE OF *VITIS VINIFERA* L. CULTIVARS IN A CHANGING CLIMATE

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Abstract:

Context and purpose of the study - Temperatures are increasing due to climate change leading to advances in grapevine phenology and sugar accumulation in grape berries. This study aims (i) to develop a temperature-based model that can predict a range of target sugar concentrations for various cultivars of *Vitis vinifera* L and (ii) develop extensive classifications for the sugar ripeness of cultivars using the model.

Material and methods - Time series of sugar concentrations were collected from research institutes, extension services and private companies from various European countries. The Day of the Year (DOY) to reach the specified target sugar concentration (170, 180, 190, 200, 210, and 220 g/l) was determined and a range of models tested using these DOYs to develop the best fit model for *Vitis vinifera* L.

Results - The best fit linear model– Growing Degree Days (parameters: base temperature (t_0) = 0°C, start date (*Tb*) = 91 or 1 April), Northern Hemisphere) – represented the model that required the least parameters and therefore the simplest in application. The model was used to characterise and classify a wide range of cultivars for DOY to reach target sugar concentrations.

The model is referred to as the Grapevine Sugar Ripeness Model (GSR). It is viticulturist- friendly as it's simple in form (linear) and its growing degree day units are easily calculated by adding average temperatures (base temperature was optimized at 0°C) derived from weather stations from the 91th day of the year (Northern Hemisphere). The classifications based on this model can inform cultivar choice as an alternative adaptation strategy to climate change, where changing cultivars may prevent the harvesting of grapes at high sugar concentrations which leads to higher alcohol wines.

Keywords: modelling, temperature, sugar, cultivars, climate change

1. Introduction

Increasing air temperatures as a result of climate change have been found to result in advanced grapevine phenology, faster accumulation of sugars through the ripening period and higher sugar concentrations at harvest or earlier harvest to maintain sugar concentrations(Jones and Davis 2000, Duchêne and Schneider, 2005, Jones et al. 2005, Jones 2006, Webb et al. 2007, Petrie and Sadras 2008, van Leeuwen and Darriet 2016). For successful grape and wine production in the context of climate change, it is important to ensure that cultivars do not ripening too early in the season because ripening during the hot summer conditions can lead to unbalanced wines with high alcohol, low acidity and reduced freshness and expression of aromas (Duchêne et al. 2010, van Leeuwen and Seguin, 2006). It could be envisaged that cultivars currently adapted to growing regions today may no longer be suitable in the future if the ripening phase and sugar accumulation do not align under warmer climate conditions.

To successfully adapt cultivars to future climate conditions, precise knowledge of their time of phenology and the timing of ripeness is important. Previous research has classified 95 cultivars for the time to flowering and 104 cultivars for the time to veraison using a temperature based phenological modelling approach (Parker et al. 2013). Less progress has been made in terms of modelling time to ripeness. Although historical records of harvest dates have been used successfully to evaluate past climate dynamics (Chuine et al. 2004, García de Cortázar-Atauri et al. 2010, Cook and Wolkovich 2016, Molitor et al. 2016) and could be used for study of climate change impact on cultivar suitability, they are often specific to a those cultivars in specific production areas and do not exist for all cultivars (Jones and Davis 2000, Tomasi et al. 2011, Daux et al. 2012). Another concern with understanding the time of ripeness is that there is no universal definition or measure to determine the "Harvest, Berries ripe" stage 38 on the modified Eichhorn and Lorenz scale of phenology (Coombe, 1995) (stage 89 in the BBCH scale). However, as sugar concentrations are objective, can be measured in all varieties and are a key indicator in grapes for the impacts of increasing temperatures during the growing season due to climate change, they represent a trait important to quantify for cultivar suitability.

Preceding classifications of varieties for maturity include maturing groupings (Jones 2006, Gladstones, 2011) and one temperature-based approach - that of thermal time to reach 200g/l using the Huglin model (Huglin, 1978). However, there is now the opportunity to develop and evaluate developing such groupings for a wider range of processed-based phenological models to determine the thermal summation of a greater number of cultivars to reach target sugar concentrations.

This study aims (i) to develop a temperature-based model that can predict a range of target sugar concentrations for various cultivars of *Vitis vinifera* L and (ii) develop extensive classifications for the sugar ripeness of cultivars using the model.

2. Material and methods

Database

Sugar concentration time series-Time series of sugar concentrations (g/L or conversion to g/L of other sugar scales or measurements such as soluble solids where applicable) were collected from research institutes, extension services and private companies from various European countries. For each time series (site x year x cultivar combination), the Day of the Year (DOY) to reach the specified target sugar concentration (170, 180, 190, 200, 210, 220 and 230 g/L) was determined by two-point linear interpolation of the two data points either side of the target sugar concentration. 90% of the data was used for model calibration and 10% of the data for validation.

Temperature data- Daily minimum and maximum temperatures were collected from meteorological stations and used to calculate the arithmetic daily mean temperature. The following criteria were set: the meteorological station was within five-kilometre distance and ±100 metre altitude range from the corresponding sugar data site; the data provider verified that the temperature data was representative for the site.

Model development and evaluation

Five different model types (GDD model, Sigmoid model, Chuine model, Richardson model and Wang and Engel model) and 21 different parameterisations (in total) were tested representing different assumptions of the plant response to the temperature. Models were fitted using the optimization algorithm of Metropolis following Chuine et al. (1998) and the Phenological Modelling Platform (PMP v5.4) (Chuine et al. 2013). The daily mean temperature was tested for all models and the best linear GDD model was selected using three statistical criteria: 1) the model efficiency i.e. percentage of variance explained (*EF*; Nash and Sutcliffe, 1970), where a negative value indicates that the model performs worse than the null model (mean of all observed dates where berries reached a target sugar concentration), and a value above zero indicates the model explains more variance than the null model (with a maximum value of 1); 2) the Root Mean Squared Error (*RMSE*) which gives the mean error of the prediction in days; 3) the Akaike Information Criterion (*AIC*; Burnham and Anderson, 2002; equation 4). The best linear model is presented herein, and the thermal summation value (*F**) for each cultivar was optimised for the best linear GDD model and each sugar concentration and the 95% confidence interval determined (using the method in Parker et al. 2013). Figures were plotted using Sigmaplot 12 (Systat Software, Inc., USA).

Classification

Up to 15 cultivars most represented in the database were classified for the time reach the target sugar concentrations of 170 g/l and 200g/l.

3. Results and discussion

3.1. Best fit linear GDD model

The best fit linear GDD model across all target sugar concentrations corresponding to GDDs starting on the 91st day of the year (t_0 = 91, Northern hemisphere) calculated using a base temperature (*Tb)* of 0°C. This model has been termed the Grapevine Sugar Ripeness (GSR) model had a greater efficiency than the other commonly published models of GFV, Huglin and Winkler across all DOY to target sugar concentrations (170-220g/L, Figure 1). For the Huglin (1978) and Winkler (1962) models which have been extensively used to predict phenology in viticulture studies, the *EF* values were less than zero for all DOY to target sugar concentrations indicating that using days alone for these models performed better than using thermal summations of these models. The GSR base temperature of 0°C differs to that of Huglin and Winkler (10°C); this indicates that the extensive geographic and seasonal database used here to calibrate the phenological model has resulted in a new and improved parameterisation of the GDD function. Interestingly the base temperature is the same of that in the GFV model where there was also a large diverse dataset used to calibrate the GFV model (Parker et al. 2011). The model was developed through thorough testing in temperature input data, extensive fit processes, sensitivity analysis and validation similar to that of Parker et al. (2011) enabling a robust approach to its development.

3.2. Characterisation of the time of year to reach target sugar concentrations for different cultivars of *V.vinifera* L. using the GSR model.

Sixty –five cultivars were characterized of which the top 15 most represented cultivars in the database are presented in Figure 2 (**A** = DOY to reach target sugar concentration of 170g/L, **B** = DOY to reach target sugar concentration of 200g/l). Out of the cultivars presented in Figure 2, nine of 14 cultivars had CIs <100°C.d. for DOY to reach 170g/L, and 14 out of 14 had CIs in the range 100-200°C.d. For DOY of 200g/L, 5 out of 14 cultivars had CIs <100°C.d. for DOY to reach 170g/L, and 13 out of 14 had CIs in the range 100-200°C.d. The increase in size of confidence intervals as the sugar concentrations increased can be attributed to two aspects: (i) the number of available data points tended to decrease at higher sugar concentrations and (ii) even through temperature is a key driver of development other factors may impact on sugar accumulation - Water status (Ojeda et al. 2001, Dai et al. 2010, Martinez-Lüscher et al. 2016), CO_2 concentration (Martinez-Lüscher et al. 2016), yield (Petrie et al. 2006, Parker et al. 2014ab, 2015) and Leaf area : fruit weight ratio (Ollat et al. 1998, Poni et al. 2006, Parker et al. 2014ab, 2015) all influence the time from flowering to véraison and the rate of sugar accumulation post-véraison. Despite these factors, integrating the temperature response over the whole growing season still resulted in substantial thermal time differences between the earliest and latest cultivars in Figure 2. For example the difference in degree days between the thermal summation (*F**) of Sauvignon and Monastrell for the 170g/L sugar target is 402 °C.d, which would correspond to 20 days if calculating an average daily temperature of 20°C. Interestingly, the classifications challenge the historical notion of 'early' and 'late' cultivars - Pinot noir is typically considered an 'early' cultivar and Merlot 'mid' although they have similar thermal time to the DOY of target sugars – factors influence groupings of cultivars are the target concentrations at which cultivars are picked (e.g. Sauvignon is often picked at a lower concentration than Monastrell based on data in our database) and other parameters such as phenolics and acids; future studies could consider these parameters as well (Pons et al. 2017). However, as the results presented here have used temperature only to successfully predict the time to sugar targets for different cultivars it can be envisaged that the classification will be useful in determining cultivar suitability in current or new regions in the context of increasing temperatures due to climate change.

4. Conclusions

The GSR model was successfully calibrated to a wide range of DOY to target sugar concentrations for 65 cultivars of which 15 have been presented here. The GSR model is viticulturist-friendly in that it is easy to calculate by simply adding daily average temperatures (as Tb = 0°C) from the 91st day of the year.The GSR temperature-based model can be used to better quantify which cultivars can be adapted to future climatic conditions in current and future growing regions.

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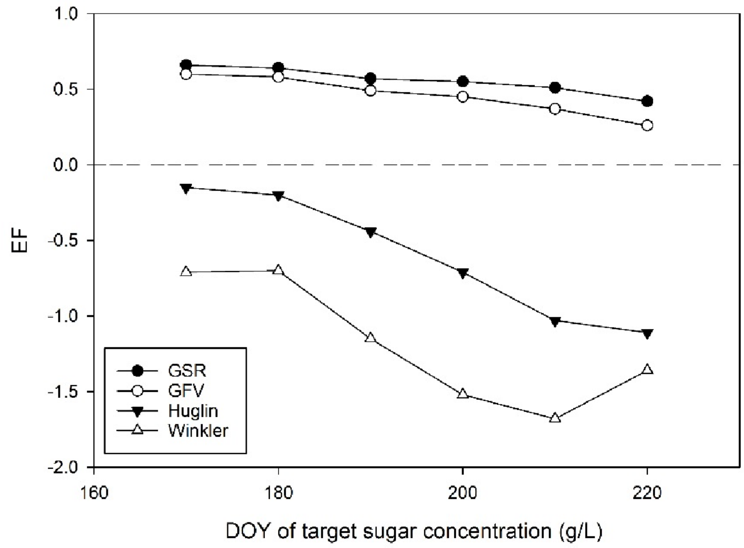
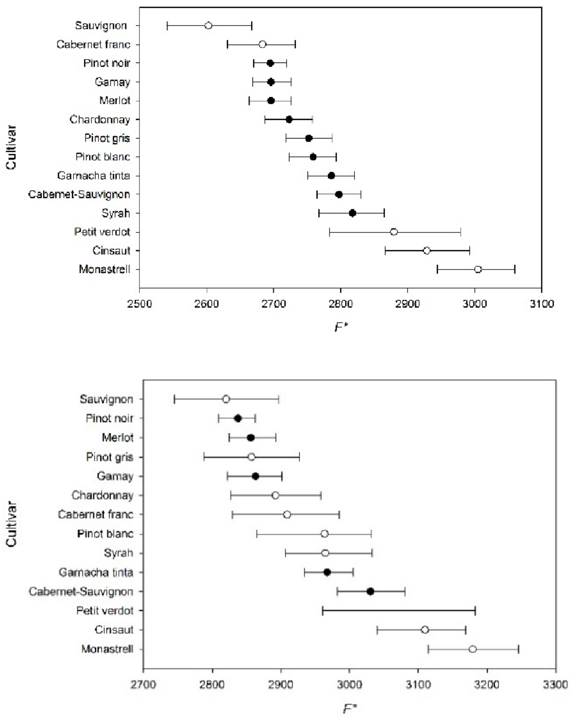


Figure 1: Model efficiency (*EF*) for the Grapevine Sugar Ripeness model (GSR, t_0 = 91, *Tb* = 0°C), the Grapevine Flowering Veraison model (GFV, t_0 = 60, *Tb* = 0°C), the Winkler model (t_0 = 91, *Tb* = 10°C), the Huglin Index (Huglin, 1978) calibrated for the day of the year to reach sugar concentrations 170-220g/l.



(A) **(B)**

Figure 2: Classification and confidence intervals (CI) of cultivars for the Day of the year (DOY) to reach sugar concentrations of **(A)** 170 and **(B)** 200g/l for the Grapevine Sugar Ripeness (GSR) model. Closed circles correspond to parameterisations where CI <100°C.d., open circles correspond to CIs in the range 100-200°C.d. and no circle corresponds to CIs in the range of 201-350°C.d.