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Grapevine Phenology of White Cultivars in Rueda Designation of Origin (Spain) in Response to Weather Conditions and Potential Shifts under Warmer Climate

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Abstract: Grapevines are among the crops that could suffer stronger effects under climate change, although the effect can differ based on cultivars and location. The aim of this work was to analyse the phenological response of the Verdejo variety compared to other two white varieties (Viura and Sauvignon Blanc) cultivated in Rueda Designation of Origin (DO), Spain, under the present climate conditions, and their potential shifts under projected climate change scenarios. Phenological dates referring to budbreak, flowering, véraison and harvest were analyzed for the period 2008–2021 in 13 plots, together with the weather conditions at daily time scale recorded during the same period. The chill and heat units were evaluated to determine the starting date for heat accumulation, as well as the base temperature to reach each phenological stage. The influence of temperature (maximum and minimum) and water availability averaged for different periods between phenological events were evaluated, and the information was used to project potential changes in phenology by 2050 and 2070 under two Representative Concentration Pathway (RCP) scenarios: RCP4.5 and RCP8.5. An advance of all phenological dates was projected, in particular for véraison and ripening. Verdejo could suffer slightly higher advance than Sauvignon Blanc, and, in any case, ripening will happen under warmer conditions. By 2050, flowering could be advanced between seven and nine days, depending on the emission scenario. However, véraison could be advanced about 13 or 14 days under the RCP4.5 scenario and between 16 and 19 days under the RCP8.5 scenario. Ripening could be reached by 2050 up to 20 days and 25 days earlier, respectively, under the RCP4.5 and the RCP8.5 emission scenarios, and up to 29 days earlier by 2070. These projections may imply further impacts on grapes and wines for the aforementioned cultivars associated to harvest under warmer conditions.

Keywords: climatic change; Sauvignon Blanc; Verdejo; Viura; temperature; water availability

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1. Introduction

Climate plays an important role in the development of the vine vegetative-productive cycle, and the trends observed over the last decade (both in temperatures and precipitations) has shown to have direct impacts on the onset and duration of phenological stages all around the world. The changes in the vegetative cycle (timing and length) have been associated to increasing temperatures [1–5], although water availability and management also influence the vine response [6–9]. However, the changes may be different depending on cultivar and location [10–13]. Each cultivar can have different thermal requirements and therefore may be affected in different ways by changes in temperature, and the cultivars with earlier phenology may suffer higher impacts in phenology and in grape composition under warming climates than those with later phenology [13,14]. In addition, an advance in phenology may lead to ripening under warmer conditions and also affect the final grape composition (acidity, sugar and phenolic composition) [14–19], and an increase in water deficit can have significant impacts on berry weight [20–23].

Each viticultural region regulates the varieties to be cultivated, which in most cases are the ones that have been traditionally grown in their vineyards and are well adapted to the climatic conditions recorded in each zone. However, under the expected changes in climate, it is needed to deepen the knowledge of the suitability of each cultivar under warmer conditions in order to maintain the sustainability of the wine sector in each area.

This research focuses on the analysis of the viticultural region under the Designation of Origin Rueda (Rueda DO) in Spain, which covers about 20,793 ha, with white varieties grown in about 98% of the surface. The wine sector is an important economic driver in the area, with 72 cellars producing about 101 mL of wine annually, 14% being for exportation. The main cultivated variety is Verdejo (86.1% of the surface), followed by Sauvignon Blanc (7.7%), Viura (3.5%) and in lower proportion other varieties such as Palomino, Viognier and Chardonnay (about 0.6% in total), within the white varieties. The red varieties represent only about 2% of the surface, with Tempranillo being the most important (1.5%) (www.dorueda.com (accessed on 14 September 2022)).

Verdejo is a variety grown in Rueda since the 11th century and the most representative of Rueda DO. The grape originated in North Africa and was possibly spread to Rueda DO by Mozarabs. It has a medium cycle length, with medium budbreak and medium-late ripening. It produces medium-sized clusters and medium-sized berries, usually spherical or short elliptical, with big seeds and thick skin and an attractive golden colour. Verdejo has a medium-high production and give wines with a wide range of intense citrus and tropical aromas, with some floral and herbaceous nuances [24].

Viura is a variety with origin in Spain, and it is the second most cultivated white grape variety in Spain, having increased its cultivated surface in the last decades. However, it is not the dominant in the study area. It is highly productive and gives rise to fruity wines with remarkable acidity. This grape variety has late budbreak and late harvest, and it is cultivated in hot and dry regions, but it is not recommended in wet environments or in zones with very dry soils, as it can suffer senescence and premature leaf fall [24].

Sauvignon Blanc is a white variety originating from the Bordeaux region of France. It produces rather small, compact and short bunches, with small berries, uniform and with medium skin thickness and a yellow-green skin colour but with very weak pigmentation of the pulp. It is sensitive to drought and considered to have late ripening, but its ripening is earlier than for the other two varieties mentioned, Verdejo and Viura. It can be grown in cool and warm climates, which lead to the development of different flavours, from aggressively herbaceous to sweetly tropical. It is medium-high productive [24].

Within the above-mentioned varieties, Viura and Sauvignon Blanc seem to be cultivated in warm and cool environments, which could support their potential suitability under warmer conditions. The shifts in phenology for Viura in areas with different climatic conditions were already analysed by Ramos [25] and Ramos and Martínez de Toda [13], and the authors pointed out the suitability of Viura, the effect of warmer conditions in the cooler region analysed and the potentiality of the areas located at higher elevation for that variety. However, little is known about the potential response of Verdejo, which is, in addition, the main variety cultivated in the study area. To contribute to this knowledge, this research analyses the variability of the phenological timing of this variety under different weather conditions recorded during the period 2008–2021 and the potential shifts that could suffer under warmer scenarios. This phenological response and phenology-climate relationships for Verdejo was compared to those for the other two varieties (Viura and Sauvignon Blanc) analysed for the same period (2008–2021), as well as the projected shifts for years 2050 and 2070 under the RCP45 and RCP8.5 emission scenarios.

2. Materials and Methods

2.1. Study Area

The Rueda DO is located in the north-central part of Spain at elevations between 700 and 930 m a.s.l. in the central sector of the depression that forms the Duero River. The vineyards are cultivated in the terraces of the Duero River and some of its tributaries (Trabancos, Zapardiel and Adaja) in soils classified as Calcic Haploxeralf, Typic Haploxeralf and Typic Xerorthent [26]. The area has a continental climate. The average annual maximum and minimum temperatures are 19.1 and 6.5 °C, respectively, and annual precipitation is about 370 mm.

2.2. Vineyard Definition

This research was based on the phenological information referring the period 2008–2021, collected in nine plots planted with Verdejo, located in Rueda (R), La Seca (LS), Nava del Rey (NR), Pozaldez (P) and Serrada (S). For the other two varieties, two plots of each variety were evaluated, which were located in La Seca for Viura and in Rueda and Ventosa de la Cuesta (VC) for Sauvignon Blanc (Figure 1). Plots were located at elevations between 718 and 770 m a.s.l. The vineyards were planted between 1980 and 2002. In the area, both Gobelet and vertical trellis training systems can be found. Most of the analysed Verdejo and Sauvignon Blanc vines were trellised trained as a double Guyot pruning, whereas Viura plots were pruned as a double Royat cordon, with vine distances in agreement with the regulations established by the Consejo Regulador of Rueda DO (most plots were planted with 3 m × 1.5 m, although some plots were planted with 3 m × 3 m and 3 m × 1.25 m). Fifty percent of the plots were irrigated, and the other 50% were cultivated in rainfed conditions. The phenological survey was carried out in at least 50 plants at two locations in each plot. The dates at which 50% of the plants in the survey plots reached the phenological stage referred to as stage C (budbreak -BB), stage I (flowering -F) and stage M (véraison –V, defined based on color change and softening) according to Baillod and Bagiollini [27], as well as when they reached ripening (considered the harvest date, at which a probable alcoholic degree of 10.5 ± 0.5% was reached), were evaluated for the period 2008–2021.

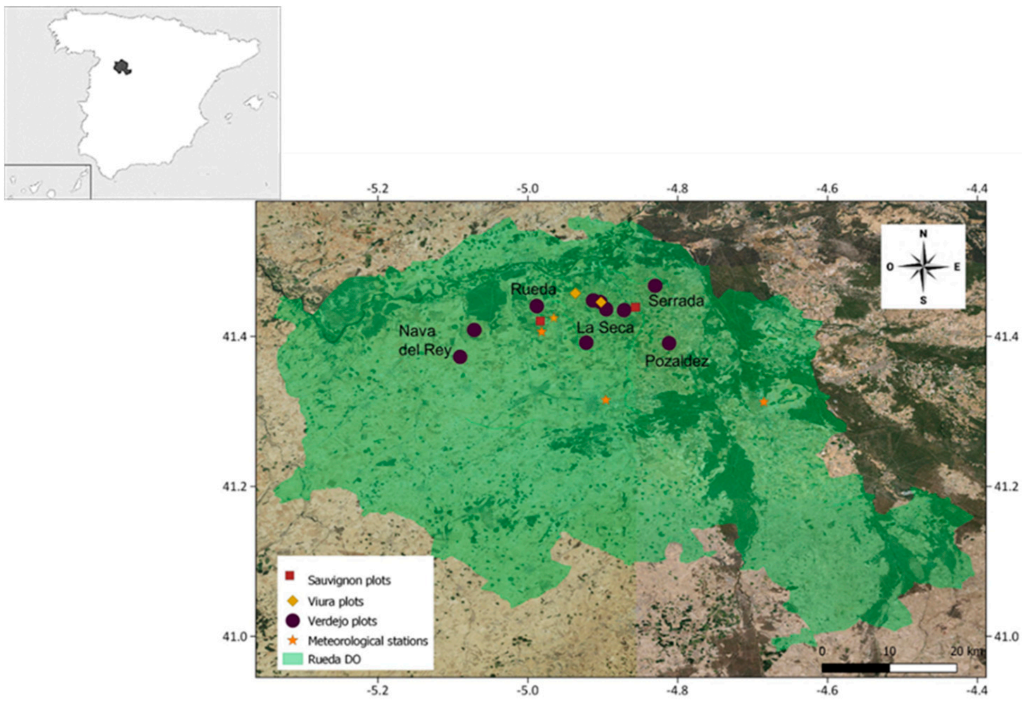


Figure 1. Location of the study area, analysed plots and meteorological stations.

The soils have organic carbon contents that varied between 6.4 and 2.18 g kg^{-1}, clay contents that range between 130 and 200 g kg^{-1}, silt contents between 170 and 279 g kg^{-1} and sand contents between 547 and 673 g kg^{-1}, whereas the coarse fraction (>2 mm) varied between 85 and 202 g kg^{-1}. The soil pH ranges between 7.9 and 8.3 (information obtained from the European Soil database (ESDAC) and the Soil Data base from JCyL).

2.3. Climate Data and Analysis

2.3.1. Current Climate

The weather conditions recorded during the period of study (2008–2021) were evaluated from the daily information recorded at Rueda (4°58′54″ W, 41°24′22″ N, 709 m) and Medina del Campo (4°53′45″ W, 41°18′55″ N, 726 m), which belongs to Junta de Castilla y León (JCyL). In order to evaluate the homogeneity of the series and to fill the small number of gaps, other series were used: Rueda (4°57′38″ W, 41°24′49″ N, 724 m), which belongs to Agencia Estatal de Meteorología (AEMET) and Olmedo (4°41′6″ W, 41°18′45″ N, 740 m), which belongs to JCyL. The information included daily temperature (maximum (Tmax) and minimum (Tmin)) and precipitation (P) recorded, as well as the reference evapotranspiration (ETo, estimated according to Penman Monteith equation). Crop evapotranspiration (ETc) was estimated using the crop coefficients proposed by Allen and Pereira [28], and an index to estimate water availability was calculated as the precipitation minus crop evapotranspiration (P-ETc). The daily information was averaged for the growing season (GS: budbreak-ripening) and for periods between phenological events (BB-F: budbreak to flowering; F-V: flowering to véraison: V-Mat: véraison to ripening). In addition, for the same period, hourly temperatures were considered in order to evaluate the thermal requirements (chill and heat units during the dormant period and until reaching budbreak), which were carried out following the procedure described in Ramos [25]. The information was obtained from the same meteorological stations. Daily chill accumulation (in Chill Portions) was calculated according to the Dynamic Model [29] using hourly temperature data, and heat accumulation (in Growing Degree Hours—GDH) was calculated according to Anderson et al. [30], using a base temperature of 4 °C and an optimum temperature of 26 °C [31]. The chill and heat phases were delimited, taking into account the relationship between budbreak dates and the means of 10 days of daily chill and heat units from 1 November (of the preceding year of recorded budbreak) to 30 April, using a Partial Least Squares (PLS) regression. Once it was determined the date at which a critical amount of chill units was reached, heat accumulation started, and the heat units were accumulated, considering the optimal base temperature (Tb) for each stage. That base temperature for each stage was estimated following the procedure described in Ramos [24], considering:

$$\mathrm{GDD} = \sum_{1}^{n}(\mathrm{Ti} - \mathrm{Tb})\cdot \mathrm{n} = \sum_{1}^{n}(\mathrm{Ti}\cdot\mathrm{n} - \mathrm{Tb}\cdot\mathrm{n}) \quad (1)$$

where Ti is the average daily temperature, Tb is the base temperature and n the number of days to reach the corresponding phenological stage. If Ti < Tb then Ti = Tb and no GDD were accumulated. The Tb values were obtained through an iterative process until reaching the temperature that minimized the standard deviation for the Growing Degree Days (GDD), which was done using the Generalized Reduced Gradient (GRG) in the SOLVER tool (Microsoft Office Excel, v16.0, Microsoft Corporation, Redmond, WA, USA).

GDD were accumulated since the determined starting date. The agreement between the observed and predicted dates using the accumulated GDD was analysed using the root mean square error (RMSE) (Equation (2)), and the Willmott index of agreement (d) [32] Equation (3). A top threshold limit in the temperature was established (Tmax = 26 °C, the same that was already mentioned in the delimitation of chill and heat units). Four non irrigated plots of Verdejo located at S, L and R were considered for this analysis, using two plots for calibration and two for validation. For the other two varieties, one plot was used for each purpose.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{1}^{n}(\mathrm{DOYs} - \mathrm{DOYo})^{\,2}}{\mathrm{n}}} \quad (2)$$

$$\mathrm{d} = 1 - \frac{\sum_{1}^{n}(\mathrm{DOYs} - \mathrm{DOYo})^{2}}{\sum_{1}^{n}\left[(\mathrm{DOYs} - \overline{\mathrm{DOYo}}) + (\mathrm{DOYo} - \overline{\mathrm{DOYo}})\right]^{2}} \quad (3)$$

2.3.2. Projected Climate

The temperature and precipitation under future climate change emission scenarios (RCP4.5 and RCP8.5) projected for 2050 and 2070 were analysed. The information referred to five models (CSIRO-Mk3-6-0 (res: 1.875 × 1.875), HadGEM2-ES (res: 1.2414 × 1.875), IPSL-CM5A-MR (res: 1.2587 × 2.5), MIROC5 (res: 1.4063 × 1.4063) and MRI-CGCM3 (res: 1.125 × 1.125)) and was obtained using the MarkSim™ DSSAT weather file generator (http://gismap.ciat.cgiar.org/MarkSimGCM/docs/doc.html (accessed on 8 July 2022)), which works with a 30 arc-second spatial resolution derived from WorldClim. The projected daily maximum and minimum temperature and precipitation obtained with the ensemble of models were used. The thermal requirements (GDD accumulated from the budbreak onset) considering the base temperature for each stage (commented in Section 2.2) were calculated to evaluate the potential advance in the phenological dates. The average heat accumulation obtained in the experimental period was used to determine the date at which each phenological stage would be reached, which allows for determining the changes in timing under different climate change scenarios.

2.4. Phenology–Climate Relationship Analysis

The relationship between phenology and climatic variables was analysed for each variety by multiple regression analysis with the forward stepwise method, using the Statgraphics Centurion software. Different variables related to temperature (Tmax and Tmin) and water availability (index = P-ETc) referring to the growing season and to the periods between phenological stages were included in the analysis. The observed relationships, together with the projected changes in temperature and precipitation, were taken into account to project potential shifts under climate change scenarios.

3. Results

3.1. Variability in the Weather Conditions Recorded in Rueda DO in the Period 2008–2021

The period analysed included years with different weather conditions, both related to temperatures and precipitation. The average Tmax and Tmin for the growing season (TmaxGS and TminGS) were 26.8 °C and 12.2 °C, respectively. Precipitation in the growing season (PGS) was on average 110 mm, which represented about 26% of the annual precipitation (Figure 2a). Within the growing cycle, there were also high variability in the Tmax and Tmin recorded. The average Tmax and Tmin in periods between phenological events can be observed in Figure 2b. For P, despite the low values recorded during the growing season, there were differences among years in its distribution along the cycle (Figure 2c).

3.2. Phenology Variability in the Period 2008–2021

The phenological dates observed during the period analysed can be observed in Figure 3. For Verdejo, budbreak, flowering and véraison took place, respectively, on April 18 ± 9 days, June 11 ± 9 days and August 15 ± 6 days, whereas ripening was reached on September 20 ± 6 days. Viura had a slightly later phenological timing than Verdejo, with budbreak on April 23 ± 8 days, flowering on June 14 ± 8 days and véraison on August 21 ± 7 days, reaching ripening at similar dates (September 22 ± 5 days). On the other hand, Sauvignon Blanc had slightly earlier phenology than Verdejo, in particular in the later stages (véraison and ripening), with budbreak on April 18 ± 8 days, flowering in June 10 ± 9 days and véraison on August 9 ± 6 days, reaching ripening on September 10 ± 7 days; thus, it is about 10 days before for Sauvignon Blanc than for Verdejo, on average. The standard deviation in the dates for all stages confirmed the high variability from year to year. For all three varieties, the earliest dates were recorded in the year 2017, whereas the later dates were in years 2008 and 2013. Within each year, the differences between locations were relatively small, as denoted the standard deviation values. In order to know if the weather conditions could explain the observed differences among years, the relationships between climatic variables and phenological dates were analysed for each variety, considering the plots from each variety together.

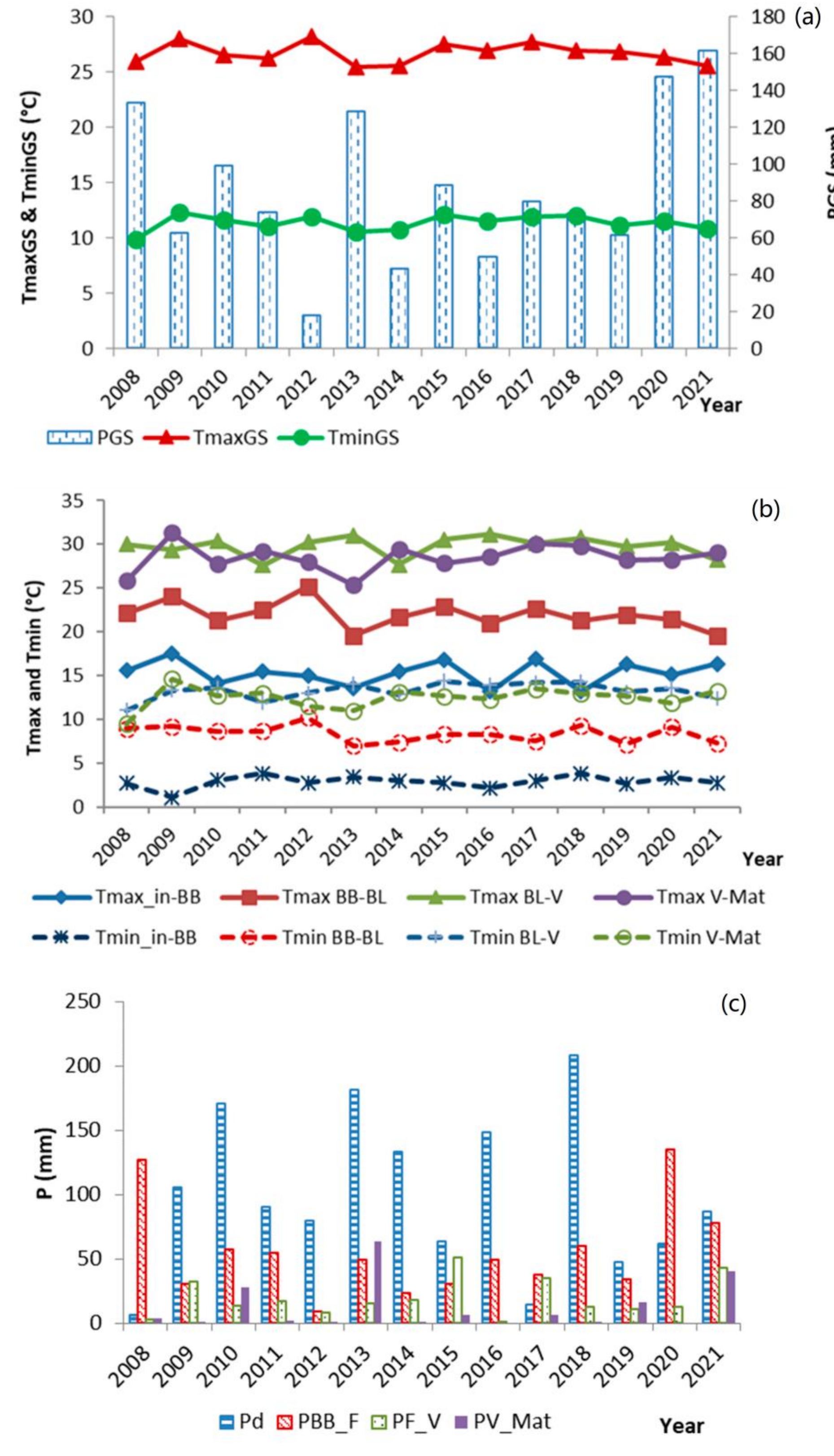
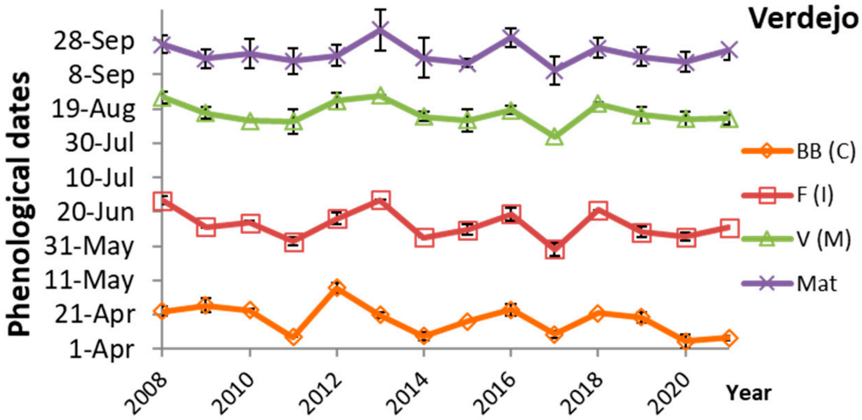
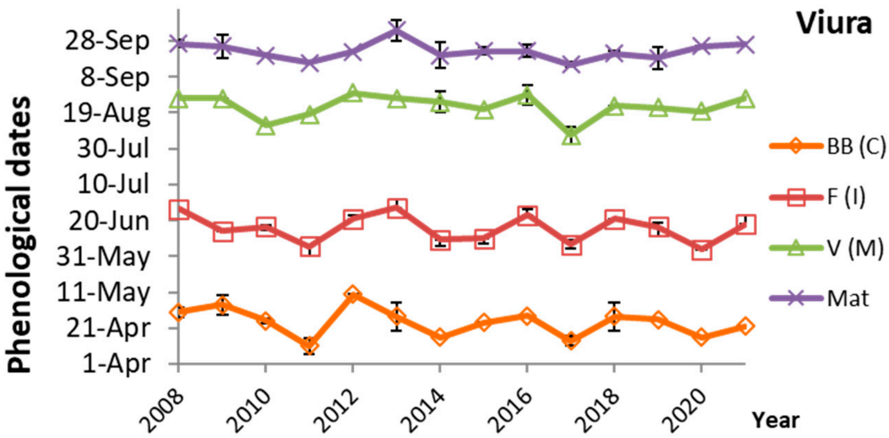


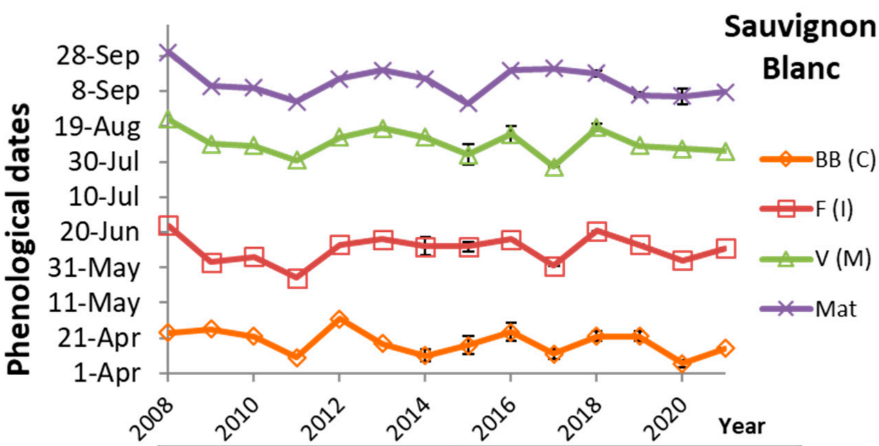
Figure 2. Variability in the climatic variables recorded in Rueda DO (Spain) during the period 2008–2021 (data from Rueda meteorological station). Average maximum (Tmax) and minimum (Tmin) temperatures and precipitation (P) for the growing season (**a**) and for different periods along the growing cycle (**b**,**c**). (GS. Growing season; d: period from 20 March to budbreak: BB-F: budbreak to flowering; F-V: flowering to véraison; V-Mat: ripening period).



BB	F	V	Mat
Apr 17±9	Jun 12±8	Ago 16±6	Sep 20± 6



BB	F	V	Mat
Apr 24 ±8	Jun 15 ±7	Ago 22 ±7	Sep 20± 6



BB	F	V	Mat
Apr 18±7	Jun 10±8	Ago 9±7	Sep 12± 8

Figure 3. Variability in the phenological timing (stages C, I, M, according to Baillod and Baggiolini [26]) and ripening (harvest date) for the analysed varieties (Verdejo, Viura and Sauvignon Blanc) in Rueda DO, during the period 2008–2021.

3.3. Climate–Phenology Relationships

The influence of temperature and water availability on phenology was evaluated, taking into account the mean, maximum and minimum temperatures recorded in the periods budbreak to flowering, flowering to véraison and véraison to ripening, as well as the values corresponding to the period previous to budbreak (the period since the date at which heat units started the accumulation to budbreak onset). In addition, water availability (P-ETc) in the same periods was included in the analysis. The variable related to temperature that better fit the phenological timing varied among varieties and stages, but, in all cases, it was confirmed that increasing temperatures (mean, maximum or minimum) lead to an advance of the phenological dates (Table 1). Budbreak and flowering were mainly driven by the temperatures recorded before budbreak, whereas the dates for véraison and ripening, when the effect of temperature was significant, depended on the temperature recorded just in the previous period, and the variable related to temperature described a high percentage of the variance. Regarding the effect of water availability (P-ETc), it was observed that an increase in water deficits during ripening advanced maturation. However, the effect of water availability on the previous stages was opposite or there was not significant effect. The term related to water availability described a lower percentage than those relative to temperature in the later stages, when, in addition, water inputs are scarce. However, water availability described a higher percentage of variance for the earlier stage (Table 1).

Table 1. Climatic variables that correlated significantly in a multiple regression analysis with phenological dates for the three analysed varieties (Verdejo, Viura and Sauvignon Blanc) in Rueda DO. (Tm: mean temperature; Tmax: maximum temperature; Tmin: minimum temperature; P-ETc: precipitation minus crop evapotranspiration; D: dormand period; in-BB: period from 20 March to budbreak; BB-F: period budbreak to flowering; F-V: period flowering to véraison; V-Mat: ripening period, between véraison and ripening).

C (Budbreak)		I (Flowering)		M (Véraison)		N (Ripening)	
Verdejo							
$R^2 = 0.511$		$R^2 = 0.680$		$R^2 = 0.451$		$R^2 = 0.670$	
P-ETc $_{D}$ Tm in-BB	− *** (27.8%) − *** (23.3%)	Tm $_{in\text{-}BB}$	− *** (57.7%)	P-ETc $_{F\text{-}V}$ Tmax $_{F\text{-}V}$ Tmin $_{F\text{-}V}$	− *** (15.7%) + *** (17.6%) − ** (11.8%)	Tmin $_{V\text{-}Mat}$ P-ETc $_{V\text{-}Mat}$	− *** (59.2%) + *** (7.8%)
Viura							
$R^2 = 0.673$		$R^2 = 0.556$		$R^2 = 0.383$		$R^2 = 0.598$	
Tm $_{in\text{-}BB}$ P-ETc $_{D}$	− *** (42.0%) − *** (25.3%)	Tm $_{in\text{-}BB}$	− *** (55.6%)	P-ETc $_{F\text{-}V}$	− ** (38%)	P-ETc $_{F\text{-}V}$ Tmax $_{V\text{-}Mat}$	− ** (19.56%) − *** (40.2%)
Sauvignon Blanc							
$R^2 = 0.730$		$R^2 = 0.468$		$R^2 = 0.413$		$R^2 = 0.553$	
Tm $_{in\text{-}BB}$	− *** (73%)	Tm $_{in\text{-}BB}$	− *** (46.8%)	P-ETc $_{F\text{-}V}$	− ** (41.3%)	P-ETc $_{F\text{-}V}$ Tmin $_{V\text{-}Mat}$	− ** (16.3%) − *** (38.9%)

(***: significant at 99%; **: significant at 95%)

For Verdejo, the stage C seems to be advanced, on average, 6.6 days for an increase 1 °C in the mean temperature in the previous month to the budbreak onset, and that change produces, in addition, an advance of about 10 days in the stage I (flowering). On the other hand, an increase of 1 °C in the average temperature during ripening produced an advance of about four days in the ripening dates. The change ratio was confirmed with similar results in the four locations analysed. The effect of increasing temperature on véraison was not as clear, probably due to the opposite effects that maximum and minimum temperature seemed to have, but it was observed that an increase of 1 °C in Tmin during the period flowering to véraison produced an advance of 1.6 days in the véraison date, although with higher variability between locations (between 0.5 and 2.7 days per 1 °C). The analysis of the influence of the available water on ripening, considering the index P-ETc, confirmed a delay in the ripening dates of about 2.6 days for an increase in 10 mm of available water in the ripening period. However, véraison seemed to suffer a delay of 1.9 days with an increase in 10 mm in water available in the period flowering to véraison.

3.4. Projected Changes in Temperature and Precipitation

The projected changes in temperature and precipitation for 2050 and 2070, under the RCP4.5 and RCP8.5 emission scenarios, in relation to the reference period 1970–2000, are shown in Table 2. The changes are expressed in °C for Tmax and Tmin and in mm for P. It can be observed that for the months corresponding to the growing season, Tmax could increase about 3.4 and 4.3 °C by 2050, respectively, under the RCP4.5 and RCP8.5 scenarios, and precipitation in the that period could decrease in about 34 and 39 mm, respectively, which represents about 40% of reduction of the already scarce precipitation recorded at present. The predicted changes in temperature are higher for the months corresponding to the periods flowering to véraison and véraison to ripening, whereas the decrease in precipitation could affect the earlier phases more than ripening. Considering the projections of temperature, the potential evapotranspiration could also increase, leading to higher water deficits.

Table 2. Projected changes in the monthly mean temperatures (maximum and minimum) and in precipitation by 2050 and 2070 under the RCP4.5 and RCP8.5 scenarios in Rueda DO.

Scenario	Year	Variable	January	February	March	April	May	June	July	August	September	October	November	December
RCP4.5	2050	TMax (°C)	1.8	1.9	1.7	2.2	2.8	3.3	3.8	3.7	3.4	2.8	2.1	1.7
		TMin (°C)	1.4	1.2	1.1	1.2	1.6	2.4	3	3.1	2.8	2.1	1.4	1.3
		P (mm)	−6.9	1.0	−4.0	−6.1	−5.9	−8.3	−9.4	−9.3	−1.3	−5.4	−5.1	−3.6
	2070	TMax (°C)	2.3	2.3	2.2	2.5	3.4	4.0	4.5	4.5	4.3	3.3	2.5	2.1
		TMin (°C)	1.7	1.4	1.6	1.5	2.2	3.0	3.6	3.8	3.5	2.5	1.6	1.7
		P (mm)	−1.9	0.9	−5.6	−9.6	−9.3	−8.4	−9.8	−8.9	−4.9	−9.1	−3.5	−3.2
RCP8.5	2050	TMax (°C)	2.3	2.5	2.3	2.8	3.6	4.1	4.6	4.8	4.3	3.5	2.7	2.2
		TMin (°C)	1.7	1.5	1.3	1.5	2.3	3.1	3.6	3.7	3.5	2.6	1.9	1.8
		P (mm)	−3.1	−3.5	−7.9	−10.5	−9.7	−8.6	−9.8	−8.0	−3.2	−8.7	−3.8	1.3
	2070	TMax (°C)	3.3	3.4	3.2	3.8	5.4	6.0	6.6	6.6	6.4	5.1	3.8	3.3
		TMin (°C)	2.5	2.4	2.1	2.4	3.3	4.5	5.3	5.4	5.5	3.9	2.9	2.8
		P (mm)	−7.9	0.9	−5.8	−13	−17.3	−13.7	−9.1	−10	−3.5	−11.3	−4.9	−2.1

3.5. Thermal Requirements to Reach Each Phenological Stage and Projected Shifts in Phenology

The analysis of the chill and heat units in the partial regression analysis showed that heat accumulation started on 20 March, on average, which was in agreement with the critical amount of chill units (100 CHU) that was observed in previous research by Ramos [25] and Andreoli et al. [33]. Table 3 shows the base temperatures and the average accumulated temperatures observed during the study period, as well as the statistics that confirmed the validation of the model to estimate the dates using the proposed procedure. The base temperature, when heat accumulation started on 20 March, was around 5 °C for budbreak, flowering and véraison for all three varieties and slightly smaller for ripening. The RMSE and d values showed moderate to good fits between observed and predicted dates, with differences between two and six days. Thus, the average GDD values were used to project the advance in the phenological dates for each stage. The projected shifts for 2050 and 2070 under the two analysed scenarios are shown in Table 4. An advance of all phenological stages is expected, being greater for véraison and ripening than for earlier stages. Flowering could be advanced between seven and nine days by 2050, depending on the emission scenarios. However, by 2050 véraison could be advanced about 13 or 14 days under the RCP4.5 scenario and between 16 and 19 days under the RCP8.5 scenario, whereas ripening could be reached up to 20 to 25 days earlier.

Table 3. Base temperature (Tb) and GDD accumulated from DOY = 80 (20 March) to reach budbreak, flowering, véraison and ripening for each variety. RMSE (root square mean error) and d (Willcott index) of the fit between observed and estimated dates obtained in the validation processes.

Variety		**BB**	**F**	**V**	**H**
Verdejo	Tb	5.4 °C	5.4 °C	5.8 °C	4.9 °C
	GDD	127 ± 36	660 ± 56	1765 ± 75	2365 ± 80
	RSME	5.41	3.70	6.10	5.90
	d	0.85	0.95	0.84	1.0
Viura	Tb	5.4 °C	5.4 °C	5.7 °C	4.4 °C
	GDD	162 ± 24	665 ± 36	1882 ± 100	2484 ± 92
	RSME	3.10	2.53	5.87	5.10
	d	0.97	0.98	0.89	0.99
Sauvignon Blanc	Tb	6.1 °C	5.7 °C	5.4 °C	3.4 °C
	GDD	104 ± 23	619 ± 52	1593 ± 53	2471 ± 77
	RSME	3.72	3.61	3.10	4.98
	d	0.92	0.95	0.98	0.99

Table 4. Projected advance (in days) of each phenological stage for each variety for RCP4.5 and RCP8.5 scenarios by 2050 and 2070 (BB: budbreak; F: flowering; V: véraison; Mat: ripening (harvest)).

Emission Scenario	**Variety**	**Year**	**BB (Days)**	**F (Days)**	**V (Days)**	**Mat (Days)**
RCP4.5	Verdejo	2050	−7 ± 1	−7 ± 1	−13 ± 2	−20 ± 2
		2070	−8 ± 1	−8 ± 2	−15 ± 5	−23 ± 3
	Viura	2050	−6 ± 1	−7 ± 2	−14 ± 2	−18 ± 3
		2070	−7 ± 2	−10 ± 3	−18 ± 3	−22 ± 4
	Sauvignon Blanc	2050	−8 ± 1	−7 ± 1	−13 ± 2	−15 ± 5
		2070	−9 ± 1	−10 ± 2	−16 ± 3	−18 ± 4
RCP8.5	Verdejo	2050	8 ± 1	−9 ± 2	−16 ± 4	−25 ± 3
		2070	−8 ± 2	−15 ± 2	−22 ± 7	−27 ± 4
	Viura	2050	−8 ± 2	−11 ± 3	−19 ± 2	−23 ± 3
		2070	−14 ± 2	−16 ± 3	−25 ± 3	−29 ± 3
	Sauvignon Blanc	2050	−9 ± 1	−11 ± 2	−18 ± 2	−19 ± 4
		2070	−11 ± 2	−16 ± 4	−24 ± 4	−24 ± 5

4. Discussion

4.1. Present and Projected Climate and Its Influence on Phenology

The period analysed (2008–2021) included years with different characteristics. Differences of up to 3.6 °C in Tmax and up to 3.4 °C in Tmin were recorded among years, which could be of the same order of magnitude as the projected changes under future climate (Table 2). For P in the growing season, there was also high variability among years (40–180 mm) in relation to the average values (110 mm). In addition, high variability in the rainfall distribution along the growing cycle was recorded (Figure 2c). Growing season precipitation represents about 30% of the annual precipitation, and the projections point out a decrease precipitation during the whole year, but the decrease in the growing season could represent 50% of the annual reduction (Table 2). Both increasing temperatures and decreasing precipitation will lead to higher water stress, which could impact grape development.

4.2. Climate Influence on Phenology

The analysis of the chill and heat phases allowed determining the base temperatures for each of the analysed varieties and the time from which heat accumulation started. It was found that heat accumulation started at middle March or in the late third of that month (20 March), which was slightly later than the observed for white varieties studied in warmer areas [24] but similar to that observed in other viticultural areas, relatively close to the study area, in which the main cultivated varieties are red varieties [34]. However, the base temperature was similar to that found by other authors [24,35]. There were not important differences in the base temperatures for the three cultivars, and the thermal requirements were similar for Verdejo and Viura and slightly smaller for Sauvignon Blanc.

Among the varieties analysed in this research, Sauvignon Blanc presented the earliest phenology, in particular earlier véraison and ripening, and Viura was the one with slightly later phenological timing than Sauvignon Blanc (up to 12 and 14 days, respectively, on average), whereas Verdejo had a response quite similar to Viura (Figure 1). The high variability in the weather conditions recorded during the period analysed allowed extracting information about the climatic variables that have higher impact on phenology as well as the effect of its variability along the growing cycle on the phenological response. The earliest phenological dates were observed in the hottest years (years 2012 and in particular in 2017), whereas the later dates were recorded in the cooler and wettest years (years 2013 and 2018), although in other years the weather characteristics recorded in specific periods seemed to drive the dates at which some stages were reached. The advance in the phenological stages in the hottest year in relation to the average ranged between 12 and 18 days and between the hottest and the coolest year ranged between 24 and 34 days. These results could give a first idea of the potential shifts under warmer scenarios.

The analysis of the relationship between phenology and climate variables confirmed the variables and the periods that can have higher influence on each phenological stage. Temperature in the previous period to the phenological event seemed to have higher influence than water availability in most of stages. The exception was véraison, which was the stage that showed poorer fits for all three varieties. For that stage, temperatures had a significant influence only for Verdejo, and there was an opposite effect of maximum and minimum temperatures. In addition, the effect of available water was opposite in the ripening period than in previous periods. In the ripening period, an increase in water deficit produced an advance of ripening, whereas increasing water deficits in the previous periods produced a delay of flowering and véraison. The advance of ripening with increasing water deficits has been observed in other varieties [33] and agrees with that indicated by Castellarin et al. [36] regarding the acceleration effect that water deficits have on ripening.

In addition, mild or moderate water deficits generally favour the berry accumulation of sugar, whereas severe water stresses can lead to significantly reduced berry quality (sugar, aroma) and grape yield [37,38]. Water stress in the phase between berry formation and the start of véraison could be critical for yields [21], although when it happens near harvest it may reduce dry matter production and cause early leaf abscission [39]. Although the yield analysis was not done plot by plot in this research, the information recorded in Rueda DO confirmed the impact of water availability on yield. Thus, grape yield for Verdejo was not only lower in the warmest years of the series analysed (like years 2012 and 2017, in which yield were up to 20% lower than the average), but also in years that recording temperatures close to the average suffered significant water deficits in the periods between flowering to véraison and between véraison to ripening, e.g., years 2009 or 2019, in which yields were about 10% lower than the average (data provided by the Consejo Regulador of Rueda DO, www.dorueda.com (accessed on 20 October 2022). The results showed that increasing water deficits in the period before véraison had higher influence on yield than those during ripening. The decrease in yield for each 10 mm increase in the water deficits was estimated in 114, 95 and 132 kg ha^{-1}, respectively, for Verdejo, Viura and Sauvignon Blanc, whereas for the same variation in water deficit during ripening, the yield decrease was estimated in 99, 95 and 129 kg ha^{-1}, respectively.

4.3. Projected Shifts of Phenology in Rueda DO under Warmer Scenarios

The projected changes in phenology showed for this research were based on thermal requirements to reach each stage and the base temperature for each stage, which have given good agreement between observed and predicted phenological dates, as the RMSE and d- Willmott values suggest. The results showed advances in the dates of all stages for the three varieties under the different scenarios (Table 4), which were higher for véraison and ripening than for earlier stages. The same behaviour has been pointed out for other areas [40]. The results project an advance for 2050 under the RCP4.5 scenario of about seven days for budbreak and flowering, about 13–14 days for véraison and up to about 20 days for harvest. Despite the small differences between varieties, Verdejo seems that it could suffer a slightly higher advance of ripening than Sauvignon Blanc, which it is at present the variety with earlier harvest. Under the RCP8.5 scenario, the advances could be up to 37% and 25% higher, respectively, for véraison and ripening. The observed effect of water availability on phenology could modify slightly the projections. Nevertheless, the obtained results were in line with the aforementioned results observed in years with different weather conditions and with the timing recorded in other areas with warmer climate. For example, for Verdejo in La Mancha, budbreak is recorded on April 16 $\pm$ 9 days, flowering takes place on May 31 $\pm$ 5 days, véraison takes place on Aug 4 $\pm$ 5 days and ripening is reached on Aug 24 $\pm$ 7 days [41]. Similarly, it can be confirmed the earlier phenology for Sauvignon Blanc in that area in relation to the study area considered in this research, with budbreak on April 9 $\pm$ 9 days, flowering on May 30 $\pm$ 4 days, véraison on July 27 $\pm$ 3 days and ripening is reached on August 17 $\pm$ 10 days. For Viura, comparing different areas where the variety is cultivated in Spain, budbreak tends to be on April 16 $\pm$ 8 days in La Mancha and on April 6 $\pm$ 9 days in Penedès, and ripening is reached, on average, on September 3 $\pm$ 5 days in la Mancha and on August 30 $\pm$ 7 days in Penedès [24,40]. However, in other areas with cooler climate, like in Rioja, the differences were smaller (budbreak on 15 April and ripening on 21–30 September) [13]. The projected shifts are slightly greater than the proposed for some of the same analysed varieties in warmer areas. Thus, for Viura cultivated in the Penedès, the projected advance for budbreak, flowering and véraison by 2050 is, respectively, about 3, 6 and 9 days under the RCP4.5 scenario and about 6, 9 and 11 days under the RCP8.5 scenario, whereas harvesting under the same scenarios by 2050 was projected to be advanced 12 and 14 days, respectively [24]. The higher advance in cooler environments agrees with results pointed out in other researches [5,11,40]. Chacón-Vozmediano et al. [11] found smaller advance in warmer than in cooler areas. Hall et al. [5] projected advances in the average harvest date that ranged from 24 to 62 days for the warmest and coolest areas, respectively, and, in the same line, Cafarra and Eccel [40] simulated more pronounced advances at higher elevations, where cooler conditions can be found.

The advance of the phenological timing could imply, in addition, a shortening of the periods between phenological events. The period flowering to véraison could be up to 10 days shorter, whereas the ripening period could suffer a decrease of about five days. Similar results have already confirmed in other viticultural areas [23,42,43]. All these results indicate that ripening will occur not only earlier but under warmer conditions, mainly during August, which could have effects on grape ripening and on grape composition and yield. Water stress in the periods between flowering and véraison and between véraison and harvest, which could even increase under warming climate, seems to have significant impacts on yield. In this respect, Yang et al. [44] analysed the importance of water stress in those periods and how it could affect yield in viticultural areas around Europe, which agrees with the aforementioned effects of water deficit on yield in the study area and with the effects of water stress on yield indicated by van Leeuwen et al. [38]. Thus, the reduction in water availability, in particular in the periods between flowering and harvest, in which rainfall is usually scarce and could even more limited in the future, could represent a threat for the sustainability of the grape production in the area.

5. Conclusions

The variability in phenology of white varieties cultivated in Rueda DO observed in years with different climatic characteristics, together with the differences related to phenological dates observed in warmer viticultural areas, allows extracting information about potential shifts under future warming scenarios. All three varieties could suffer an advance of all phenological events, in particular véraison and ripening. Verdejo could suffer slightly higher advance than Sauvignon Blanc, and, in any case, ripening will happen under warmer conditions. In addition, the reduction in water availability, in particular in the period between flowering and véraison, will lead to higher water stress, which, in case they are not properly balanced with irrigation, could affect grape yield. This suggests the need of establishing suitable strategies of management to maintain the sustainability of the grape production in the sector.

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