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RESEARCH ARTICLE

Projected effects of climate change on Tempranillo and Chardonnay varieties in La Mancha Designation of Origin

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Abstract

Climate is one of the components of terroir that most influences grape growth and development. Vines might suffer significant impacts under climate change, although they can be different depending on the variety and location. The aim of this study was to analyze vine phenology and grape composition variability related to weather conditions in La Mancha Designation of Origin, in Spain, and potential changes caused by climate change. The research focuses on the Tempranillo and Chardonnay varieties. Phenological dates and grape composition at ripening were evaluated for the period 2000–2019 and related to climatic variables. This information was used to project the potential variations under different emission scenarios (Representative concentration pathways RCP4.5 and RCP8.5) for 2050 and 2070. An advance in phenology is projected under climate change, for the two varieties, in agreement with that observed in years with different weather conditions. The advance for 2050 could be of 6, 11, 9, and 8 days for Tempranillo and 4, 9, 9, and 10 days for Chardonnay, respectively, for bud break, flowering, veraison, and maturity under the RCP4.5 scenario, and up to 50% higher under the PCP8.5 scenario. This advance in the phenological timing will imply ripening under warmer conditions, which could affect grape quality. A decrease in titratable acidity in both varieties is projected due to the increasing temperatures, which would have negative implications for the two varieties, and anthocyanin concentrations in Tempranillo are projected to suffer changes due to variations in temperature and in water deficits. The research presents a novelty for La Mancha DO, where there is no previous analysis in this respect. This is the first study in this vine-growing region in which projections are made on the potential changes for aforementioned vine cultivars, whose response is analyzed for expected warmer conditions in relation to those observed in cooler areas.

Keywords Acidity · Anthocyanins · Climate change · Chardonnay · Temperature · Tempranillo · Water deficit

1 Introduction

The concept of “terroir” refers to the environmental conditions of a specific place, where the grapes are grown and which give a wine its distinctive character. Climate is one of its most important components as it influences grape growth and development. During the dormant period, vines need some chilling hours, while during the growing season, they require the accumulation of heat units for the grapes to reach maturity. However, the presence of an excess of days with extreme temperatures, both cold and warm, may negatively affect grape development and final composition (Greer and Weedon 2014).

In view of the trends in temperatures recorded during the last decades, various studies have already shown a trend of earlier phenology and harvest in different viticultural areas, although the degree of change may not be the same in all zones and for different varieties (Bock et al. 2011; Fraga et al. 2016; Ramos et al. 2018; among others). In addition, climate variability also influences grape composition and quality (Bock et al. 2011; Nistor et al. 2018).

Each cultivar is suited to a given temperature range (Jones 2012) and temperatures define the suitability of each area for growing specific cultivars. Thus, under the expected changes in temperature under climate change scenarios, the suitability of each variety may change. Warmer scenarios may have a negative effect on the suitability of some areas for a specific

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variety and give rise to productivity losses (Morales-Castilla et al. 2020; Wolkovich et al. 2018). Given the period needed for vines to establish and reach production, and in order to devise appropriate strategies to mitigate the effects of climate change on them, further information about potential changes should be obtained in zones with different climatic characteristics, taking into account the potential changes in temperature and precipitation that may occur in such areas. In this respect, different approaches have been applied in order to project changes in phenology (Caffarra and Eccel 2010; Fraga et al. 2016; García de Cortázar-Atauri et al. 2009; Parker et al. 2011; Ramos 2017; Webb et al. 2007), and in grape quality (Pieri et al. 2012; Van Leeuwen et al. 2017), among others.

Two varieties of broad interest around the word were selected in this research (Tempranillo and Chardonnay). The *Vitis vinifera* cultivar Tempranillo is a red wine grape variety from Spain, which is the fifth most cultivated variety in the world covering some 231,000 ha, with a tendency to increase (OIV 2017). Eighty-eight percent of total area grown with this variety is cultivated in Spain, which accounts for 20.8% of the vineyard area and about 50% of the red varieties cultivated in the country. Tempranillo has an early bud break and early ripening with a short growth cycle. It is sensitive to extreme drought, and in warm climates, it can produce wines with high alcohol content and low acidity. On the other hand, Chardonnay is a white grape variety from Burgundy that covers about 210,000 ha in more than 40 countries. It is cultivated in France, Italy, and Spain, but the USA, Australia, and Chile are the biggest producers. In Spain, this variety accounts for about 1.75% of the vineyard area, but the surface is also increasing. Among white varieties, this one has an early bud break and early maturity, and it has the potential to produce aromatic wines that age well.

The response of these varieties was analyzed in La Mancha Designation of Origin (DO) (Spain), which is the largest delimited viticultural area in Europe (157,449 ha). In this area, the effect of climate change on vineyards could have particular relevance due to the high thermal range of temperatures and projected changes (Gaertner et al. 2012). Tempranillo accounts 30,196 ha, and represents for more than 69% of the cultivated area of the red varieties. Chardonnay occupies about 1,500 ha. Compared to other varieties, both have early ripening, which means that it occurs under warm conditions. Both varieties, which have a short cycle and early ripening, could be more sensitive to temperature changes than those with late ripening (Ramos et al. 2018).

The objective of this study was to evaluate the phenological timing and grape composition of these two varieties under the present weather conditions recorded in La Mancha and potential changes under warmer conditions that could occur under climate change scenarios. Climate change is expected to modify grapevine phenology and further grape composition. However, these changes could be different under different climatic conditions, which might change in different way the suitability of an area to grow a given variety. Under this hypothesis, the final objectives were to confirm: (1) how Tempranillo and Chardonnay grapevine phenology might be modified under warmer conditions in this specific area of Spain; (2) how grape composition and, in particular, the acidity of the two varieties might be affected, and (3) if climate change might modify the suitability of the study area for these two varieties taking temperature and water deficit changes into account.

2 Material and methods

2.1 Study area

The research was performed in plots, which can be considered representative of the vineyards in La Mancha Designation of Origen (DO), belonging to the Instituto Regional de Investigación y Desarrollo Agroalimentario y Forestal (IRIAF). The plots were located at 663 m.a.s.l. (latitude: 36.170500 N, longitude: 3.004975 W) (Fig. 1), and were planted with the Tempranillo and Chardonnay varieties. The soils are classified as *Calcixerept petric.* In the plots under study, the soils are shallow (< 40cm depth), well drained, with about 40% of coarse elements and loam to sandy-clay-loam textures (46.6% sand; 32.2% silt; 2.12% clay) and 3.2% of organic matter content (Amorós-Ortíz-Villajos et al. 2015). The area has a temperate climate with high differences in temperature between winter and summer. According to the Winkler index, this area is classified as Region IV and it records scarce rainfall during the year (about 350 mm), with less than 50% occurring in the vine growing season.

2.2 Data and analysis

2.2.1 Weather information and climate projections

The weather information used in this research was recorded at the Argamasilla de Alba weather station, which belongs to the network of the Spanish Ministry for Agriculture, Fisheries and Food. The data were completed when necessary taking into account information recorded in Tomelloso, from a weather station that belongs to the State Meteorological Agency (Agencia Estatal de Meteorología—AEMET). Daily temperature (maximum, minimum, and mean), precipitation, and potential evapotranspiration (estimated according to Penman Monteith) for the period 2000–2019 were analyzed. From this information, the average daily temperature [maximum (Tmax), minimum (Tmin) and mean (Tm)] referring to the growing season (GS: bud break to maturity) for both varieties and some bioclimatic indexes such as Winkler (WI) and Huglin (HI) indexes were calculated. In addition, hourly

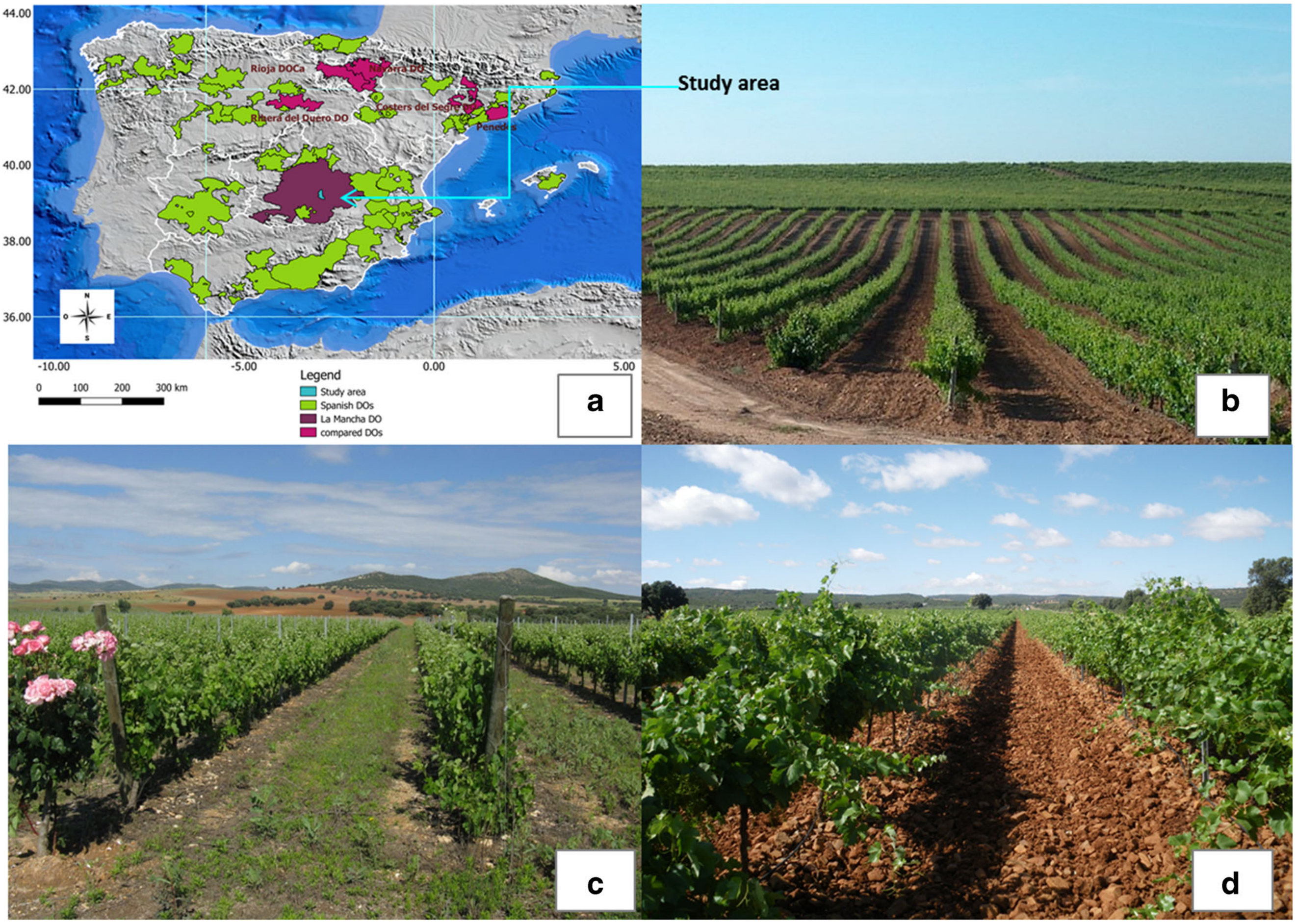

Fig. 1 Location and view of vinegrowing landscapes in La Mancha D.O: the study area: (a) Location of La Mancha DO and study area; (b) typical view with large extensions of vineyards; (c and d) view of the topography of the area and vineyards with different management (with soil vegetation cover and with bare soil)

maximum and minimum temperatures for the same period were used to determine heat requirements, as described in Section 2.2.3. Precipitation recorded during the growing season and in each period between phenological events and crop evapotranspiration in each period were also calculated in order to analyze vine response to available water. The crop coefficients proposed by Allen and Pereira (2009) for vines that suffer some water stress, and in agreement with results obtained under similar conditions in the region (López-Urrea et al. 2012) with values of 0.3, 0.7, and 0.55, for Kc initial, Kc mid, and Kc end, respectively, were considered in the calculation of crop evapotranspiration, with a value of 0.4 at flowering, 0.65 at veraison, and 0.7 when maturity was reached.

The daily temperature and precipitation under future climate change emission scenarios (RCP4.5 and RCP8.5) were projected for 2050 and 2070 using the average of 20 replications of an ensemble of 17 models (BCC-CSM1-1; BCC-CSM1-1-M; CSIRO-Mk3-6-0; FIO-ESM; GFDL-CM3; GFDL-ESM2G; GFDL-ESM2M; GISS-E2-H; GISS-E2-R; HadGEM2-ES; IPSL-CM5A-LR; IPSL-CM5A-MR; MIROC-ESM; MIROC-ESM-CHEM; MIROC5; MRI-CGCM3 and NorESM1-M). The information was obtained using the MarkSim™ DSSAT weather file generator (http://gismap.ciat.cgiar.org/ MarkSimGCM/docs/doc.html), which works with a 30 arc-second spatial resolution derived from WorldClim.

2.2.2 Vine phenology and grape composition

The information used in this research referred to two series (2000–2019) for each variety and information from another two/three plots in half of the years for each variety. The plants were between 4 and 17 years old during the period analyzed; they were trained in double cordon with a planting pattern of 2.8–3 m between rows and 1.2–2.1 m between plants. The vines were cultivated under irrigated conditions but maintaining some stress, due to the water limitations in the area. Vines were irrigated using a drip irrigation system, applying low doses of water before veraison, in order to limit the growth of the berry. The starting date of irrigation was stablished based on predawn leaf water potential (Ψ_{PD}) measurements made using a Scholander chamber. Irrigation began when the vines had used most of water reserves (-0.5 MPa $\leq \Psi_{PD} \leq$ -0.4 MPa), which, depending on the years, occurred between the second and fourth week of June. Then, water was applied to cover between 20 and 25% of plant's water needs, which implied performing five–seven irrigations of five–six mm each, separated 4 days between them. In post-veraison, the applied irrigation volumes covered between 25 and 30% of the vine needs, to avoid compromising a good ripening of the grapes, which meant five–seven irrigations of eight–ten mm each, separated 4 days between them. The applied irrigation doses represented 100–120 mm per year, on average. This strategy allowed respecting the maximum limits of 1500 m^3 ha^{-1} of irrigation water imposed by the Guadiana Hydrographic Confederation for the area, being still a margin of response in case of higher water needs.

In order to analyze the influence of available water on the vines, a water deficit index defined as precipitation plus irrigation minus crop evapotranspiration (P+R-ETc) was considered in the analysis. Vine phenology of the two varieties, related to bud break, flowering, veraison, and maturity, was analyzed for the period 2000–2019. Bud break, flowering, and veraison corresponded to the stages C, I, and M defined according to Baillod and Baggiolini (1993). The dates given for bud break, flowering, and veraison for each variety corresponded to the date at which 50% of a sample of vines of each variety in the field had reached the phenological stage. Lots of four vines were examined at each time and variety, with the same criteria along the analyzed series. The date for maturity was defined based on the amount of soluble solids in the must (°Brix). Although the value at harvesting can vary depending on the final purpose, during the period analyzed, both the Tempranillo and Chardonnay grapes of the analyzed plots were used for wine-making and the soluble solids, = 22.0–24.5 °Brix, were considered.

Grape composition, including pH, titratable acidity (AcT), and malic acid (AcM), was analyzed for all plots and years according to the official OIV methods (OIV 2004), and total and extractable anthocyanins (AntT and AntE) were also analyzed for the Tempranillo variety using the Glories method (Saint-Criq de Gaulejac et al. 1998), in years with contrasting weather conditions (in the period 2000–2004 and 2017–2019). Each analysis was carried out in samples of 200 berries taken from the central and lower part of the clusters. The information was supplied by the IRIAF.

2.2.3 Vine response and climate relationships

The thermal requirements to reach each phenological stage at present were calculated for each variety. Firstly, the chilling and warming periods were identified by analyzing the daily chill and heat accumulations from the dormant period following the methodology described in Ramos (2017). Daily chill accumulation (in Chill Portions) was calculated according to the Dynamic Model (Fishman et al. 1987) using hourly temperature data, and heat accumulation (in Growing Degree Hours) was calculated according to Anderson et al. (1986), using a base temperature of 4°C and an optimum temperature of 26°C (Parker et al. 2011). The chill and heat phases were delimited taking into account the relationship between bud break dates and the means of 10 days of daily chill and heat units from October 1 (of the preceding year of recorded bud break) to April 30, using a Partial Least Squares (PLS) regression. PLS regression is useful when there are more predictors than variables and it has been already used in the identification of chilling and heat requirements (Luedeling et al. 2013; Guo et al. 2015). Negative correlation coefficients were interpreted as periods that brought bud break forward. Having delimited the chill and heat phases, the thermal requirements, expressed in growing degree days (GDD), needed to reach each phenological stage, were calculated.

The accumulated temperatures in each period between phenological stages were considered, and the optimal base for each period temperature was estimated following the methodology applied by Ramos (2017). The accumulated degree days were calculated as the difference between the daily mean temperature and the base temperature critical for effective heat accumulation (Tb) recorded from the given starting date. The base temperature (Tb) for each stage was estimated following the procedure described in Ramos (2017) (eq. 1), through an iterative process until reaching the temperature that minimized the standard deviation for GDD, which was done using the Generalized Reduced Gradient (GRG) in the SOLVER tool (Microsoft Office Excel).

$$GDD = \sum_1^n (Ti - Tb) = \sum_1^n Ti - Tb \cdot n, for\ Ti > Tb\ and\ no\ accumulation\ when\ Ti \leq Tb \qquad (1)$$

where Ti is the average daily temperature, Tb is the base temperature, and n the number of days to reach the corresponding phenological stage.

The starting point of the analysis for all stages was the date obtained in the partial regression analysis and it was the one used to set the base temperature for bud break. In addition, a threshold limit in the maximum accumulated temperature was established. In this respect, two values were checked: Tmax=26°C, which was already mentioned in the delimitation of chill and heat units, and Tmax=22°C as indicated by Gladstones (2011) and Molitor et al. (2014).

The agreement between the observed and predicted dates was analyzed using the root mean square error (RMSE) (eq.2), and the Willmott index of agreement (d) (Willmott et al. 2011) (eq. 3), where DOYs and DOYo are the simulated and observed dates at which the corresponding phenological event occurs, respectively.

$$RMSE = \sqrt{\frac{\sum_1^n (DOYs - DOYo)^2}{n}} \quad (2)$$

$$d = 1 - \frac{\sum_1^n (DOYs - DOYo)^2}{\sum_1^n \left[\left(DOYs - \overline{DOYo} \right) + \left(DOYo - \overline{DOYo} \right) \right]^2} \quad (3)$$

The average heat accumulation value at which each phenological stage was reached for each variety was considered to determine the changes in timing under different climate change scenarios taking into account the projected temperatures obtained in Section 2.2.1.

In addition, in order to analyze the relationship between climatic variables and grape composition, a multiple regression analysis was performed using the forward stepwise method for each variety, using Statgraphics Centurion. Different variables related to temperature (Tmax, Tmin, and GDD) and available water (water deficit index = P+R-ETc) referring to the growing season and to the periods between phenological stages were included in the analysis. The GDD values for GS and for each period included in the regression analysis were the accumulated GDD during the period with Tb=0 and a maximum temperature limit 22°C. The observed relationships between grape composition and climate variables together with the projected changes in temperature and precipitation were taken into account to project potential changes under climate change scenarios.

3 Results and discussion

3.1 Weather conditions

The present research was carried out in an area that records high temperatures during the last half of the growing cycle and high variability from year to year. According to the information recorded in the area, the growing season (period bud break to maturity) was determined for each year (dates described in Section 3.2). The average growing season temperatures for the period analyzed (2000–2019) varied between 20.6°C and 24.1°C for Tempranillo, and between 18.7°C and 22.2°C for Chardonnay, which means differences of 3.5°C between years within the period of analysis and 1.8°C between the two varieties. The maximum growing season temperatures varied between 27.8°C and 31.5°C for Tempranillo and between 25.5°C and 30.7°C for Chardonnay, while the minimum growing season temperature varied between 11.6°C and 15.3°C and between 9.8°C and 13.9°C, respectively, for Tempranillo and Chardonnay (ESM_1.pdf). Jones (2012) indicated an optimum temperature range of 16.0°C–18.5°C for Tempranillo and 14.0°C–17.5°C for Chardonnay during the period April–October, in which the growing season of these varieties takes place. During the analyzed years, in the study area, the average temperatures recorded for the period April–October ranged between 18.9°C and 22.0°C. This means that these varieties are being cultivated in the study area at present under warmer conditions than those found in the literature as being optimal for their cultivation. Thus, this response of the vines in relation to that recorded in cooler areas could give information as to the potential effects of climate change. With the observed temperatures, the WI ranged between 1727 and 2333 GDD with average values of 1985 GDD, and the HI ranged between 2430 and 3011 GDD, with average values of 2712 GDD. The annual precipitation (referring to the hydrological year Oct-Sep) displayed high variability from year to year, ranging between 171.1 and 622.6 mm, of which less than 50% was recorded within the growing season. Precipitation in the bud break to maturity period varied between 35.4 and 232.0 mm for Chardonnay and between 46 and 180 mm for Tempranillo (ESM_1.pdf).

3.2 Phenology

As a result of temperature variability, grapevine phenology also presented high variability from year to year for the varieties (Tempranillo and Chardonnay) examined in this research. For the period under study, the average phenological dates were April 16 ± 7 days and April 5 ± 6 days for bud break, May 31 ± 6 days and May 27 ± 5 days for flowering, July 26 ± 6 days and July 25 ± 6 days for veraison, and Aug 23 ± 11 days and Aug 17 ± 9 days for maturity, respectively, for Tempranillo and Chardonnay. These average dates were considered the phenology at present, which were compared with the projected dates in order to quantify the advances. The highest differences in phenological timing between years for both varieties were recorded at bud break, and in particular for maturity. For Tempranillo, differences in bud break higher than 20 days were observed between the warmest and the coolest and wettest years. The earliest bud break took place on April 7–8 in years like 2011 or 2017 (warm years), and the latest on April 24–30, in years like 2000 or 2019. For Chardonnay, the earliest bud break dates varied from March 27 and April 1–4, (which were recorded in 2002, 2009, 2011, and 2017) to April 18 (in 2019). For maturity, the differences between years were even higher, with the earliest in 2017 (on August 4 for Tempranillo and on August 1 for Chardonnay) and the latest in 2018 (September 24 for Tempranillo and August 28 for Chardonnay). The observed differences in phenology in years with high differences in temperature could provide an initial idea of the changes expected under increasing temperatures that may occur under climate change.

When these average dates were compared with those recorded in other climatologically different Spanish wine-growing areas where Tempranillo is the main variety, it was observed that while bud break occurs on similar dates, veraison and in particular maturity were reached much earlier in La Mancha. During the last decades (period 2004–2018), it was found that bud break occurred on April 17–27, 4–17, and 6–18, respectively, in Ribera del Duero DO, Rioja DOCa, and Navarra DO, while veraison occurred on August 10-24, 9-13 and 13-27, respectively, in those areas. The dates, however, were similar to those recorded in Raimat (Costers del Segre DO) (July 21–31). Regarding maturity, based also on the date at which the same soluble solids were reached, it was also advanced in La Mancha DO in relation to the rest of the above commented areas (September 5–October 9 in Ribera del Duero DO; August 28–October 2 in Rioja DOCa, September 11–30 in Navarra DO, and September 16–21 in Raimat (Costers del Segre DO)) (information obtained from Consejo Regulador DO Ribera del Duero, Consejo Regulador DO Rioja DOCa, Consejo Regulador DO Navarra, Codorniu S.A., Raimat (personal communication), Ramos et al. 2015; Ramos et al. 2018; Leibar Palacio 2018). The results indicate that, at present, maturation in La Mancha occurs earlier and under warmer conditions than in other areas.

For Chardonnay, the dates were compared with those recorded in areas in which this variety is more extensively cultivated. In this respect, the dates for Chardonnay in La Mancha DO were compared with those observed in the Penedès DO (NE Spain) (period 1996–2012) and with additional information from Italy, at elevations between 195 and 470 m.a.s.l. Bud break, flowering, and veraison were recorded later in La Mancha DO than in Penedès (March 11–18, May10–17, July 15–20, respectively) (Ramos and Martínez-Casasnovas 2014) but earlier than in the regions of Italy indicated by Alikadic et al. (2019) (April 15, June 6, and July 26). The date of maturity could not be compared due to the final purpose of the grapes (soluble solids were different in Penedès and it was not known in the information consulted from Italy). Nevertheless, the maturity dates were similar to those in Raimat (Costers del Segre DO, August 2–23), although veraison in that area tended to occur earlier (July 10–15). Thus, for Chardonnay, the dates do not differ so much to those recorded in other areas. These results point out that the Tempranillo variety has a phenology sensitive response to temperature and changes in temperature might produce higher changes in Tempranillo than in Chardonnay.

The analysis of the chill and heat units indicated that the dates at which heat accumulation started was February 26 for Tempranillo and March 11 for Chardonnay (Fig. 2). These dates were considered the heat accumulation start dates for Tempranillo and Chardonnay, respectively. The thermal requirements, needed to reach the phenological stages analyzed, are presented in Table 1. Considering the different periods between phenological stages, the base temperatures to reach BB, BL, V, and Mat were 6.6, 6.4, 3.2, and 12.5°C for Tempranillo and 0.0, 5.5, 1.1, and 10.5°C for Chardonnay, respectively. Using these base temperatures and Tmax limited to 22°C, the GDD needed to reach the respective phases were 180±40, 431±38, 1020±55, and 259±68 GDD, respectively, for Tempranillo and 276±52, 479±33, 1207±49, and 262±72 GDD for Chardonnay. The RMSE and Willmott index (d) statistics are also shown in Table 1. These values represent moderate-to-satisfactory results. The highest errors were found for the date of maturity, and it was higher for Tempranillo than for Chardonnay.

3.3 Predicted changes in temperature and precipitation

The changes in temperature (ESM_2.pdf) predicted with the ensemble of models imply an average change in the maximum temperatures corresponding to the present average growing season (April 15 to September 15 for Tempranillo and from March 25 to August 20 for Chardonnay) of 1.7°C and 2.1°C by 2050 and 1.9°C and 3.1°C by 2070, respectively, under the RCP4.5 and RCP8.5 emission scenarios. The increase for the minimum temperatures for the same period can be between 1.3°C and 1.5 °C by 2050 and between 1.7°C and 2.4°C by 2070, respectively, under the RCP4.5 and RCP8.5 scenarios. These changes are of the same order of magnitude as those observed in 2017 in relation to the average at present (TmaxGS and TminGS in 2017 were 1.7°C and 1.2°C higher than the average during the period under study). Thus, this could be a clear example of the response by vines under change scenarios in the near future. The prediction for precipitation showed a decrease during the growing season (ESM_2.pdf). Within this period, precipitation is usually recorded in April-May-June and September, with very scarce precipitation in July and August, when higher temperatures are recorded. In the spring months, a reduction in precipitation is predicted, which vary between about 15% for 2050 under the RCP 4.5 scenario and up to 30% by 2070 under RCP 8.5. This lower water intake will imply higher additional irrigation to maintain a similar hydric status.

3.4 Projected changes in phenology under climate change scenarios

An advance in all phenological dates was projected based on the thermal requirements obtained for the varieties analyzed in the study area at present and considering predicted climate changes. The advances are shown in Table 2. Bud break for Tempranillo and Chardonnay, respectively, may undergo an advance of up to 11 and 7 days by 2070 under the warmest scenario. The advance for flowering and veraison may be higher, by up to 19 and 15 days, respectively, for

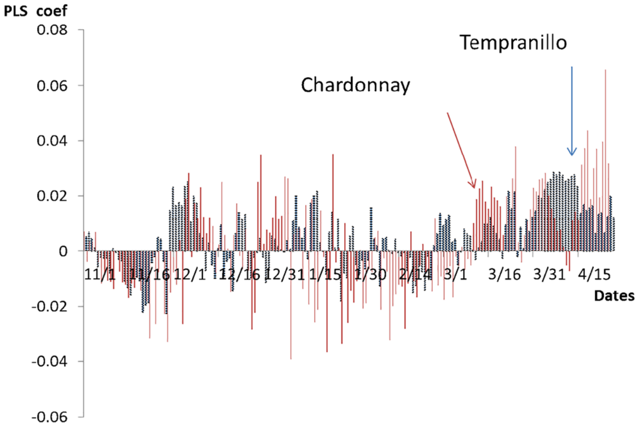

Fig. 2 Coefficients of the partial least squares (PLS) regression for the periods between November 1 and April 30 for both varieties

Tempranillo, and up to 17 and 16 days for Chardonnay, under the same scenario. Maturity could be advanced by up to 17 and 16 days, respectively, for both varieties. Thus, earlier timing was projected for flowering, veraison, and maturity than for bud break. These projections of phenology were done taken into account only thermal requirements, despite the fact that water availability can also have an effect on the phenological timing. Although a reduction in precipitation is expected, its effects were not considered in this analysis. As it was explained before, vines in the area are irrigated maintaining certain stress (as it can be seen in Fig. 3) and the irrigation dose was adjusted every year taken into account the specific environmental conditions. Under the management followed in the area, and except for the most extreme conditions (very wet or very dry years), the water deficit index varied between 100 and 200 mm in most years. Thus, it is expected that an increase in water deficit could be supplied with a higher irrigation dose reaching similar water deficits values and respecting the limitations imposed by the local regulations, due to the fact that there is still a margin of response (up to 300–500 m^3ha^{-1}) with respect to the maximum imposed by the Guadiana Hydrographic Confederation for the area. The projected advance in phenology agrees with that found in other viticultural regions (Webb et al. 2007; Pieri et al. 2012; Fraga et al. 2016; Ramos 2017; Ramos et al. 2018). Webb et al. (2007) projected in Australia by earlier bud break of 6 to 11 days in 2050 for Cabernet Sauvignon and earlier harvesting, which, depending on the regions, could be up to 45 days by 2050 under the warmer scenario. Pieri et al. (2012) indicated a potential advance of 20–40 days in the phenological calendar in some areas in France regarding Chardonnay, Merlot, and Grenache, while other areas could become more suitable for grape cultivation. Fraga et al. (2016), in Portugal, indicated an expected advance of flowering of between 2 and 6 days and an advance of veraison between 6 and 14 days, and they indicated that the influence of the thermal conditions on phenology during flowering influenced the subsequent phases. Ramos et al. (2018), for Tempranillo in other Spanish viticultural area located at higher elevation and with lower temperatures (Region Ib according to the WI and warm to warm-temperate on the HI), projected, under the RCP4.5 scenario, an advance of flowering of about 6 days by 2050 and up to 7.9 days by 2070, and an advance of veraison of about 13 and 18 days, respectively, for 2050 and 2070. However, the projected advance for maturity was higher (up to 18 and 24 days, respectively, for 2050 and 2070). For Chardonnay, cultivated in a warm area of NE Spain (Region III according to WI and temperate on the HI index), Ramos (2017), under the same scenario, projected an advance of flowering of 5.5 days by 2050 and up to 10.4 days by 2070, and an advance of veraison of about 9.2 and 12.4 days, respectively, for 2050 and 2070. Similarly, the advance projected for maturity was up to 12 and 17 days, respectively, for 2050 and 2070. Thus, the projected advance in the warmer study area analyzed in this research (Region IV according to WI), in particular for maturity, seems to be slightly lower than in cooler areas. Hall et al. (2016) also project advances in the average harvest date that, depending on climate conditions, range from 24 to 62 days for the warmest and coolest areas, respectively. Nevertheless, the results obtained would imply earlier harvest and under hot conditions, as will take place in the hottest month of the year in the study area, which could have additional effects on grape

Table 1 Heat requirements expressed in degree days (GDD) needed to reach each analyzed phenological stage for Tempranillo and Chardonnay

	Tempranillo				Chardonnay			
	Bud break (BB)	Flowering (BL)	Veraison (V)	Maturity (Mat)	Bud break (BB)	Flowering (BL)	Veraison (V)	Maturity (Mat)
	DOY58-BB	BB-BL	BL-V	V-Mat	DOY70-BB	BB-BL	BL-V	V-Mat
Tb	6.6	6.4	3.2	12.5	0.0	5.5	1.1	10.5
GDD	180±40	431±38	1020±55	259±68	276±52	479±33	1207±49	262±72
RMSE	5.540	2.533	4.503	7.616	4.764	3.096	2.860	5.627
d	0.742	0.957	0.831	0.721	0.564	0.884	0.922	0.850

Values refer to GDD accumulated in periods between phenological stages using the corresponding base temperature for each period and considering a threshold of Tmax=22°C (*DOY* day of year; *Tb* base temperature; *RMSE* root mean square error; *d* Willmott index)

Table 2 Average dates ± standard deviation (in days) and projected advance (in days) of the phenological dates (bud break, flowering, veraison and maturity) for Tempranillo and Chardonnay in La Mancha under the RCP4.5 and RCP8.5 emission scenarios

Scenario	Year	Tempranillo				Chardonnay			
		Bud break	Flowering	Veraison	Maturity	Bud break	Flowering	Veraison	Maturity
Present		16 Apr. ±7	31 May±6	26 July±6	23 Aug. ±11	5 Apr. ±6	27 May ±5	25 July ±6	17 Aug. ±9
RCP 4.5	2050	−6±3	−11±4	−9±4	−8±2	−4±2	−9±4	−9±4	−10±3
	2070	−7±3	−13±4	−11±4	−10±4	−5±3	−11±3	−11±4.	−11±4
RCP8.5	2050	−8±2	−14±5	−11±4	−13±4	−6±3	−12±4	−12±4	−12±5
	2070	−11±4	−19±4	−15±4	−17±4	−7±4	−17±5	−16±4	−16±5

ripening and composition. The warmer conditions may change the suitability of the area for some varieties and may also affect yield. As mentioned by Morales-Castilla et al. (2020) and Wolkovich et al. (2018), an increase in temperature may give rise to significant losses of suitable areas for the cultivation of a given variety in a specific region, although a gain can be produced in other areas located at higher elevation and with lower temperatures, or in areas where soils have higher water storage capacity (Ramos et al. 2020). However, changing plant material including other varieties or changing some management practices can reduce losses and help to maintain the viticultural region (Petrie et al. 2017; Zheng et al. 2017; Moran et al. 2019; van Leeuwen et al. 2019). In this respect, Moran et al. (2019) confirmed that late pruning produced a delay of bud break, flowering, and veraison that can mitigate the effects of rising temperatures. Similarly, Petrie et al. (2017) confirmed delayed pruning as a tool to delay ripening of Cabernet Sauvignon and Shiraz. Zheng et al. (2017) confirmed, in addition, that delaying pruning could improve fruit quality and decrease yield loss.

3.5 Variability of grape composition. Relationship with climatic characteristics and potential changes under climate change

During the period of analysis, grape composition at ripening presented high variability from year to year. The average values are shown in Table 3. Titratable acidity varied between 3.7 and 6.7 gL^{-1} for Tempranillo and between 4.8 and 6.9 gL^{-1} for Chardonnay, while malic acid varied between 1.2 and 4 gL^{-1} and between 1.6 and 4 gL^{-1}, respectively, for the two varieties. The lower acidity levels were recorded in the warmer years. This result is in agreement with that already indicated in recent decades in some areas (Vršič and Vodovnik 2012; van Leeuwen and Darriet 2016), which has been associated with an increase in temperature and radiation. Thus, the increase in temperature associated with climate change may imply lower acidity values in the near future.

The influence of temperature was then evaluated. Figure 3 shows the evolution of titratable acidity and malic acid, in both varieties, with accumulated degrees during ripening, which was the variable that best allowed visualizing the influence of temperature on grape quality. Other authors, however, have related the changes in acidity to changes in mean maximum and minimum temperature (Barnuud et al. 2014; Ramos and Martínez de Toda 2020). These graphs include not only the grape parameters at the date of maturity but also the changes observed during ripening.

The results showed that both titratable acidity and malic acid decreased with increasing accumulated temperature for the two varieties. In addition, a decrease in acidity is also observed with increasing water deficits (Fig. 3). However, the combined effects at ripening were quantified with a stepwise multiple regression analysis, and it was observed that variables related to temperature were the ones that gave significant fit in the final results. Accumulated temperature (GDD) during the growing season was the variable that explained higher percentage of variance. However, as GDD were used to project the future phenology and some limits were defined to reach each stage, it cannot be used to project changes in grape composition. Instead, maximum and minimum temperatures referred to different periods were considered in the analysis in order to use the results to project changes in grape composition (Table 4). Titratable acidity, malic acid, and pH at ripening were mainly driven by maximum or minimum temperature in the flowering to veraison period (BL-V). For Tempranillo, an increase of 1°C of Tmax during that period would lead to a decrease in titratable acidity of 0.28 gL^{-1}, while malic acid could decrease about 0.15 gL^{-1} for the same temperature increase. For Chardonnay, the decrease in titratable acidity was also related to Tmax in the same period and it could decrease 0.17 gL^{-1} for an increase of 1°C of Tmax, while malic acid could decrease 0.16 gL^{-1}, for an increase of 1°C of Tmax in the BL-V period. The results agree with those of Sugiura et al. (2020), who related acidity to temperatures in sensitive periods after flowering, and in particular with the increase that malic acid usually takes place just

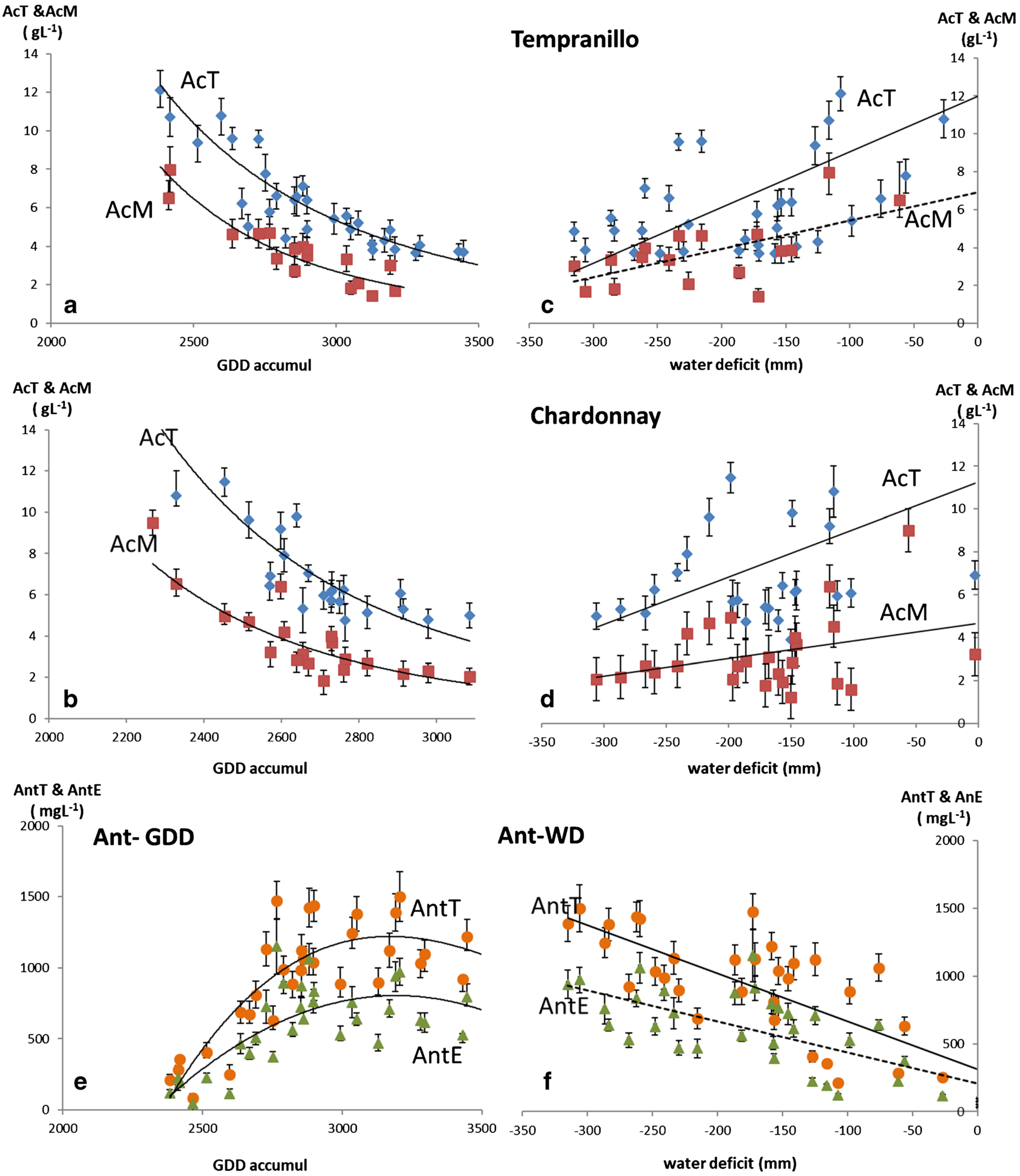

Fig. 3 Evolution of titratable acidity (AcT) and malic acid (AcM) with increasing accumulated temperatures (GDD) until reaching ripening for: (a) Tempranillo and (b) Chardonnay. Variation of titratable acidity and malic acid with water deficit for: (c) Tempranillo, (d) Chardonnay. Evolution of total and extractable anthocyanins (AntT and AntE for Tempranillo with (e) accumulated temperatures (GDD); and (f) water deficit (WD) during ripening)

before veraison (Volschenkla et al. 2006). Thus, increasing temperatures in that period will give rise to lower acid concentrations at the end of the cycle. The effects of temperature on pH were obviously opposite to those on acidity,

Table 3 Mean, maximum, and minimum values of grape composition, recorded during the analyzed period

Variety		Soluble solids (°Brix)	AcT (g/L tartaric acid)	pH	AcM (g/L)	AntT (mg/L)	AntE (mg/L)
Tempranillo	Mean	23.6	4.8	3.5	2.2	1260	824
	Std	0.7	0.8	0.2	0.6	218	190
	Max	25.4	5.3	3.8	3.8	1500	972
	Min	22.9	3.7	3.1	1.4	886	468
Chardonnay	Mean	23.2	5.8	3.4	2.6	-	-
	Std	1.6	0.7	0.2	0.7	-	-
	Max	27.0	6.9	3.8	4.0	-	-
	Min	20.5	4.8	3.1	1.6	-	-

AcT titratable acidity; *AcM* malic acid; *AntT* total anthocyanins; *AntE* extractable anthocyanins

indicating an increase of 0.04 units of pH for an increase of 1°C in the Tmax in the BL-V period for Tempranillo and 0.04 units of pH for an increase of 1°C in the Tmin in the BL-V period for Chardonnay (Table 4). Sadras et al. (2013) already confirmed the effect of increasing temperatures on acidity and the additional impacts on aromas and flavors.

Taking into account the observed relationships and the projected changes in temperature during the BL-V period (mainly in months June-July), titratable acidity will decrease by 2050, between 0.52 and 0.65 gL^{-1} in Tempranillo, and between 0.31 and 0.39 gL^{-1} in Chardonnay, respectively, under the RCP4.5 and RCP8.5 scenarios. The decrease could be of up to 0.94 and 0.56 gL^{-1} by 2070, respectively, under the warmer scenario. Malic acid will decrease between 0.28 and 0.35 gL^{-1} in Tempranillo and between 0.22 and 0.29 gL^{-1} in Chardonnay, by 2050, respectively under both scenarios. For Tempranillo, the effect of increasing temperatures could imply a decrease in acidity, slightly greater for total acidity than for malic acid (between 10 and 14% under the RCP5.4 scenario and up to 19% by 2070 under the warmest scenario). For Chardonnay, the reduction could be a little smaller than for Tempranillo and higher in percentage for malic acid (between 9 and 17%) than for titratable acidity (between 5 and 10%). Nevertheless, the changes depend on the cultivar. Barnuud et al. (2014), for some regions in Australia, projected reductions in titratable acidity of up to 40% for Chardonnay, which are higher than the projected in the study area, while for some red varieties, like Shiraz and Cabernet Sauvignon, the reduction could be of about 15% and 12%, respectively, by 2070 under a high warming scenario, which are slightly smaller than the projected for Tempranillo in this region. Regarding pH, the projected changes are of about 0.07 and 0.06 units by 2050 under RCP4.5 scenario, and up to 0.11 and 0.10 units by 2070 under the RCP8.5 scenario, respectively, for Tempranillo and Chardonnay.

The information for anthocyanins was only available for the red variety, with values of extractable anthocyanins that ranged between 526 and 972 mgL^{-1}, and total anthocyanins that ranged between 922 and 1388 mgL^{-1}, the lowest values being recorded in the hottest year of the series analyzed (i.e., 2017). In that year, in which the average temperature was nearly 2°C higher than the average in the period of analysis,

Table 4 Significant variables resulted in the multiple regression analysis between grape composition

	AcT	AcM	pH	AntT	AntE
Tempranillo	-TmaxBL-V $r^2 = 0.625$ $p < 0.003$	-TmaxBL-V $r^2 = 0.516$ $p<0.002$	TmaxBL-V $r^2=0.586$ $p<0.003$	-TmaxBL-V $r^2=0.343$; $p=0.05$ P+R-ETc V-Mat $r^2=0.36$; $p=0.0074$	-TmaxV-Mat $r^2=0.279$; $p=0.019$ P+R-ETc V Mat; $r^2=0.758$; $p=0.05$
	Change ratio −0.28 gL^{-1}/1°C	Change ratio −0.15 gL^{-1}/1°C	Change ratio 0.0 units/1°C	Change ratio −164mgL^{-1}/1°C; −49mgL^{-1}/10mm	Change ratio −96mgL^{-1}/1°C; −29mgL^{-1}/10mm
Chardonnay	-TmaxBL-V $r^2=0.62$ $p=0.0042$ Change Ratio −0.17gL^{-1}/1°C	-TmaxBL-V $r^2=0.66$ $p=0.05$ Change ratio −0.16gL^{-1}/1°C	TminBL-V $r^2=0.26$ $p=0.05$ Change ratio 0.04 units/1°C		

Related to acidity: titratable acidity (AcT), malic acid (AcM), and pH; and anthocyanins (total anthocyanins (AntT) and extractable anthocyanins (AntE) with climate variables); related to temperature: accumulated degree days (GDD), maximum and minimum temperature (Tmin and Tmax), and available water (P+R-ETc); related to different periods: *GS* growing season, *BL-V* flowering to veraison, *V-Mat* veraison to maturity anthocyanin concentration was about 25% lower than average. Figure 3 shows the evolution of total and extractable anthocyanin with accumulated temperature for the Tempranillo variety during ripening. Anthocyanins increase with accumulated temperature until reaching a maximum value, which stabilizes or decreases slightly. The multiple regression analysis showed that temperature recorded in the BL-V period and water available in the V-Mat period had significant influence on anthocyanins. Tmax recorded in the BL-V period was the variable that best fitted total anthocyanin concentrations, and the results showed that increasing Tmax values will give rise to a reduction in anthocyanins. Grape berries grown under high temperatures may have a lower abundance of some individual anthocyanins in the skins (Mori et al. 2007). Taking into account the average growing season period at present, and the changes in Tmax predicted for that period, a decrease of about 164 mgL^{-1} per 1°C increase in Tmax in the BL-V period may be recorded. Nevertheless, anthocyanin concentration also depends on available water. Total anthocyanin concentrations were related to the available water recorded in the ripening period (V-Mat), indicating that the concentration of anthocyanins increases with increasing water deficits in that period. The results showed an increase of total anthocyanins at a rate of 49 mgL^{-1} for an increase of 10 mm in water deficit during the V-Mat period. A decrease in available water leads to a reduction in berry size, and it justifies the increase in anthocyanin concentration (Ojeda et al. 2002; van Leeuwen et al. 2004). Thus, increasing water deficits, associated with an increase in temperature and to a decrease in precipitation, could somehow offset the decrease in anthocyanins produced by increasing temperatures. The high variability in rainfall distribution recorded in the area makes difficult to project changes in water deficits. Although the changes in potential evapotranspiration could be estimated for a given rainfall distribution taking into account the projected changes in climate variables, the analysis will be not representative of all situations. Thus, as already occurred at present in the study case, the irrigation dose should be controlled and adjusted every year to maintain the quality of the wines in this respect.

The results also showed the impact of temperature on extractable anthocyanins. A decrease in extractable anthocyanin is expected with increasing Tmax during the BL-V period, which could be of about 96 mgL^{-1} per 1°C increase. Similarly to the findings for total anthocyanins, water deficit also had an influence on the extractable fraction. Thus, the decrease in precipitation could also somehow affect the amount of extractable anthocyanins, increasing by about 29 mgL^{-1} per 10 mm increase in water deficit recorded during the V-Mat period. In this respect, Castellarin et al. (2007) found differences in anthocyanin extractability depending on irrigation rates and water deficits. The increase in water deficit could be supplied with additional irrigation. However, water availability is limited in the area, and irrigations doses should be studied and adjusted every year.

Based on the observed relationships and the projected changes in temperature, anthocyanins could decrease about 300 mgL^{-1} and 380 mgL^{-1} by 2050, respectively, under the RCP4.5 and RCP8.5 scenarios, and the decrease in the extractable anthocyanins could be of about 175 mgL^{-1} and 225 mgL^{-1}, respectively, under the same scenarios (Table 5). The decrease in anthocyanins in the Tempranillo variety with increasing temperatures observed in this research (between 25 and 32% for AntT and between 22 and 28% for AntE, by 2050, respectively, under the RCP4.5 and RCP8.5 scenarios, and up to 46 and 40%, by 2070, respectively, under the warmest scenario) is greater than those found for other red varieties. Barnuud et al. (2014) projected a reduction in anthocyanin accumulation in Cabernet Sauvignon under climate change, by up to 12% by 2030 and up to 33% by 2070 in the northern wine regions in Australia, while in the southern wine regions, the reductions could be smaller (up to 2 and 18% lower, respectively, in the same time periods). Ramos and Martínez de Toda (2020) also showed significant changes in anthocyanin concentrations linked to changes in temperature and available water in rainfed vineyards

Table 5 Projected changes in grape composition by 2050 and 2070 associated with temperature increase under the RCP4.5 and RCP8.5 scenarios

Variety	Scenario	Δ AcT (gL^{-1})	Δ AcM (gL^{-1})	Δ pH (units)	Δ AntT (mgL^{-1})	Δ AntE (mgL^{-1})
Tempranillo						
	RCP4.5 2050	−0.52±0.05	−0.28±0.03	0.074±0.009	−300±15	−175±12
	RCP4.5 2070	−0.63±0.07	−0.33±0.03	0.090±0.011	−369±17	−2156±18
	RCP8.5 2050	−0.65±0.07	−0.35±0.04	0.094±0.012	−380±17	−225±19
	RCP8.5 2070	−0.94±0.10	−0.50±0.05	0.135±0.014	−550±16	−320±25
Chardonnay						
	RCP4.5 2050	−0.31±0.03	−0.22±0.02	0.056±0.005		
	RCP4.5 2070	−0.37±0.03	−0.27±0.03	0.066±0.006		
	RCP8.5 2050	−0.39±0.03	−0.29±0.04	0.071±0.008		
	RCP8.5 2070	−0.56±0.04	−0.43±0.04	0.104±0.009		

AcT titratable acidity; *AcM* malic acid; *AntT* total anthocyanins; *AntE* extractable anthocyanins cultivated in two areas with different climatic characteristics. The authors showed that such changes would be nearly balanced in cooler areas, while in the warmest areas analyzed, anthocyanins could suffer significant decreases. Thus, the effect of water deficit should be combined with that of increasing temperatures and the possibility of increasing heat waves, which could affect vine growth in general. In this respect, Galat Giorgi et al. (2019) indicated that well-watered vines are better prepared to face a heat wave than water deficient vines. These results should be added to the fact that ripening will occur earlier and under higher temperature, which will give rise to unbalanced grapes (Martinez de Toda and Balda 2015; Sadras and Moran 2012). Additionally, other vine management practices, including canopy management techniques (Petrie et al. 2017; van Leeuwen et al. 2019; Zheng et al. 2017), should be applied to delay grape ripening and therefore mitigate the advances projected under warmer conditions.

The results obtained in this research present a novelty for this particular viticultural area as it is the first time that this analysis has been conducted for La Mancha DO. In addition, the results can be of broad interest as it looks at varieties cultivated all around the world. The effect that warmer conditions may have on the composition of the analyzed grape varieties is shown.

4 Conclusion

The analysis of vine phenology and grape composition of Chardonnay and Tempranillo in La Mancha DO, in a period that included years with different weather conditions, allows extracting useful information about their response to changes in temperature and water deficits. Additionally, it allows comparing the response of the selected cultivars under the warmer conditions recorded in La Mancha with that recorded in other cooler areas at present and under similar climate change scenarios. Earlier phenology for Tempranillo was confirmed at present in the study area compared to other areas where this cultivar is considered one of the main red varieties. Lesser differences were found for Chardonnay in this respect. An advance of all phenological phases is projected under increasing temperatures, but veraison and maturity are the phases most affected by changes in temperature. The projected changes are smaller than in cooler areas, but the advance will imply harvesting not only earlier but under warmer conditions, which may cause unbalanced ripening and affect grape composition negatively. The increase in temperature will produce lower acidity wines for both Chardonnay and Tempranillo varieties. This decrease will be particularly negative for Tempranillo, which is a variety with low acidity already at present. In this cultivar, anthocyanins could also be affected by increasing temperatures despite the compensation that greater water deficits could have on them. Although increasing water deficits associated with a decline in precipitation and a rise in evapotranspiration could be balanced with higher irrigation doses, this means higher production cost and higher water use, which is a scarce resource in the area. This study constitutes a novelty for this viticultural area, because this is the first in this line. It confirmed the negative impacts of climate change for the winegrowing region and in particular for Tempranillo. Thus, in order to maintain its suitability to preserve the growth of the present varieties, different practices should be applied to delay phenological timing and to maintain the balance of the grape composition and quality at harvest.

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Declarations

Conflict of interest The authors declare no competing interests.

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