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Assessment of changes in Grenache grapevine maturity in a Mediterranean context over the last half-century

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ABSTRACT

This study aims to i) evaluate some descriptive variables for Grenache berry composition over the last 50 years in the southern Rhône Valley wine-growing region and ii) analyse the impacts of climate on the main annual developmental phases of the Grenache berry to understand recent changes observed in the vineyard. A large and spatialised historical, open database from the Rhône Valley grape maturity network (1969–2020) was used to explore trends in grape profile during maturity and at harvest. Then, gridded climate data was used for processing phenological stages and ecoclimatic indicators. Significant changes in grapevine phenology and maturity dynamics were found and linked with changes to ecoclimatic indicators by carrying out a correlation analysis. Depending on the phenological phases, a limited number of ecoclimatic indicators had a significant effect on the maturity profile. The results highlight direct climate impacts on different maturity and yield variables over the last 50 years. These results provide important information about future issues in grape production and the implications for managing viticulture adaptation strategies and thus serve as a basis for assessing, prioritising and optimising technical means of maintaining current grape quality and yield.

This study uses an ecoclimatic approach for examining in detail the effects of climate change on the Grenache grape variety in a Mediterranean context. The open database provides the latest information from a large network of plots and over a long period of time, making it possible to validate many results recorded in the literature. This is the first study to use this open database and we wish this database could lead to further explorations and results in viticulture and climate change issues.

KEYWORDS: Grenache, southern Rhône valley vineyard, climate change, grapevine ripening, ecoclimatic indicators, Mediterranean climate, berry composition, open sciences, open data

INTRODUCTION

Climate change impacts the environment and agriculture in a number of ways and is a threat to the future of global wine production (see extensive literature references; for example, Santos *et al.,* 2012; Hannah *et al.,* 2013; Moriondo *et al.,* 2013; van Leeuwen *et al.,* 2013; Santillán *et al.,* 2019; Morales-Castilla *et al.,* 2020).

The warming of the last half-century has led to the observation of changes in phenological stages in almost all vineyards around the world (see Jones *et al.,* 2005, Petrie and Sadras, 2008; Dalla Marta *et al.,* 2010; Tomasi *et al.,* 2011; Bock *et al.,* 2013; Ruml *et al.,* 2016; van Leeuwen and Darriet, 2016; Cola *et al.,* 2017; García de Cortázar-Atauri *et al.,* 2017; Ramos *et al.,* 2018; Koufos *et al.,* 2020). These changes (mostly earlier events) can be observed at different intensities for all the phenological stages, as well as for harvest dates (the latter is not strictly considered as a phenological stage—see García de Cortázar-Atauri *et al.,* 2010 for further explanations). Other studies have also explored changes—over different temporal periods—in the maturity parameters of specific cultivars in local vineyards: Cabernet-Sauvignon and Merlot in Bordeaux (France) (Jones and Davis, 2000); Riesling in Alsace (France) (Duchêne and Schneider, 2005); six traditional varieties, Chenin, Melon, Sauvignon blanc, Cabernet Franc, Gamay and Grolleau, in the Loire Valley (France) (Neethling *et al.,* 2012); Shiraz in Australia (Petrie and Sadras, 2008); Tempranillo in Ribera del Duero Valley (Spain) (Ramos *et al.,* 2015a); Chasselas in Switzerland (Zufferey *et al.,* 2018); traditional and international varieties in Greece (Koufos *et al.,* 2020).

Some of the aforementioned studies measured the relationship between changes in phenological stages or quality parameters (primarily sugar and acidity and in some cases berry weight) and changes in climatic variables. For example, Neethling *et al.* (2012) showed that the historical changes in berry composition (sugar concentrations and titratable acidity) in the Loire Valley is significantly related to climate variables. Their analysis were using indicators based on temperature and rainfall evaluated during specific calendar periods: the growing cycle was considered as constant every year from April to October. In another context, Ramos *et al.* (2015a) and Ramos *et al.* (2015b) described the influence of climate and soil spatial variability in Ribera del Duero. However, the authors did not explore significant trends related to the different traits observed: this is probably because the studies took place over a period of 11 years (not long enough to observe climate trends), and that they calculated mean values for the phenological stages for the whole vineyard. Nevertheless, they showed that climate (also described in their studies using temperature and rainfall indicators) plays an important role in the annual phenology and quality.

Most of such studies, therefore, do not take into account the changes in grapevine phenology in their calculation of climate indicators. Several studies have recently shown the importance of including changes to the annual growing cycle when determining the impact of climate on various crops (see Holzkämper *et al.,* 2013; Caubel *et al.,* 2015; Caubel *et al.,* 2017). These 'ecoclimatic indicators' (i.e., agroclimatic indicators calculated during plant phenological phases) can accurately account for the effects of climatic variables between the different phenological stages, especially under changing climatic conditions. Nevertheless, this approach is often confronted with a lack of phenological data over the periods studied. In such cases, the only possibility is to use process-based models adapted to the studied variety to supply the missing information (Costa *et al.,* 2019; Marjou and García de Cortázar-Atauri, 2019; Morales-Castilla *et al.,* 2020), taking into account their uncertainties to perfectly simulate all the phenological stages (especially budburst) (Chuine *et al.,* 2016).

Another limitation of current studies is the number of climatic variables explored. There is extensive literature on the effect of weather (climate) variables on quality and yield compounds (for example see Coombe and Iland, 2004). Nevertheless, most of the studies which explore these relationships in climate change conditions are mainly based on temperature analysis (minimum, average or maximum). Only a minority use variables such as rainfall and evapotranspiration to describe the water status of the plant. However, other variables such as solar radiation, wind or humidity are usually considered as very important for grapevine growth and quality (van Leeuwen and Darriet, 2016); however, they are generally not explored, mainly because it is difficult to access this type of observation over long periods of time in the same areas where phenological or quality data have been obtained.

Finally, the diversity and representativeness of the data can also be a limiting factor when analysing changes to certain variables in the face of climate change. Most studies give datasets on one or a limited number of plots, which may in some cases limit the possibilities of extrapolating some of these results to other regions or other varieties. Moreover, most of the studied data series only describe values for maturity and yield compounds at harvest and they do not allow for any changes in dynamics.

The present study sought to explore some of these limitations. A large open database was used, which was created by the wine inter-professional association (Inter Rhône) of the Rhône Valley vineyard, one of the main vineyards of the European Mediterranean area. The database integrates data from maturity monitoring which has been carried out on a network of plots since the end of the 1960s. This study focused on Grenache, the main variety cultivated in the Rhône Valley, to explore i) the changes in a number of descriptive quality and yield variables over the past 50 years, ii) the link between these changes and a large set of climate indicators; the latter was calculated based on the main phenological stages (using the ecoclimatic indicator method) using reanalysed mesoclimate data from the SAFRAN Météo-France database, which provides daily data for several climate variables for the same period and iii) how this information

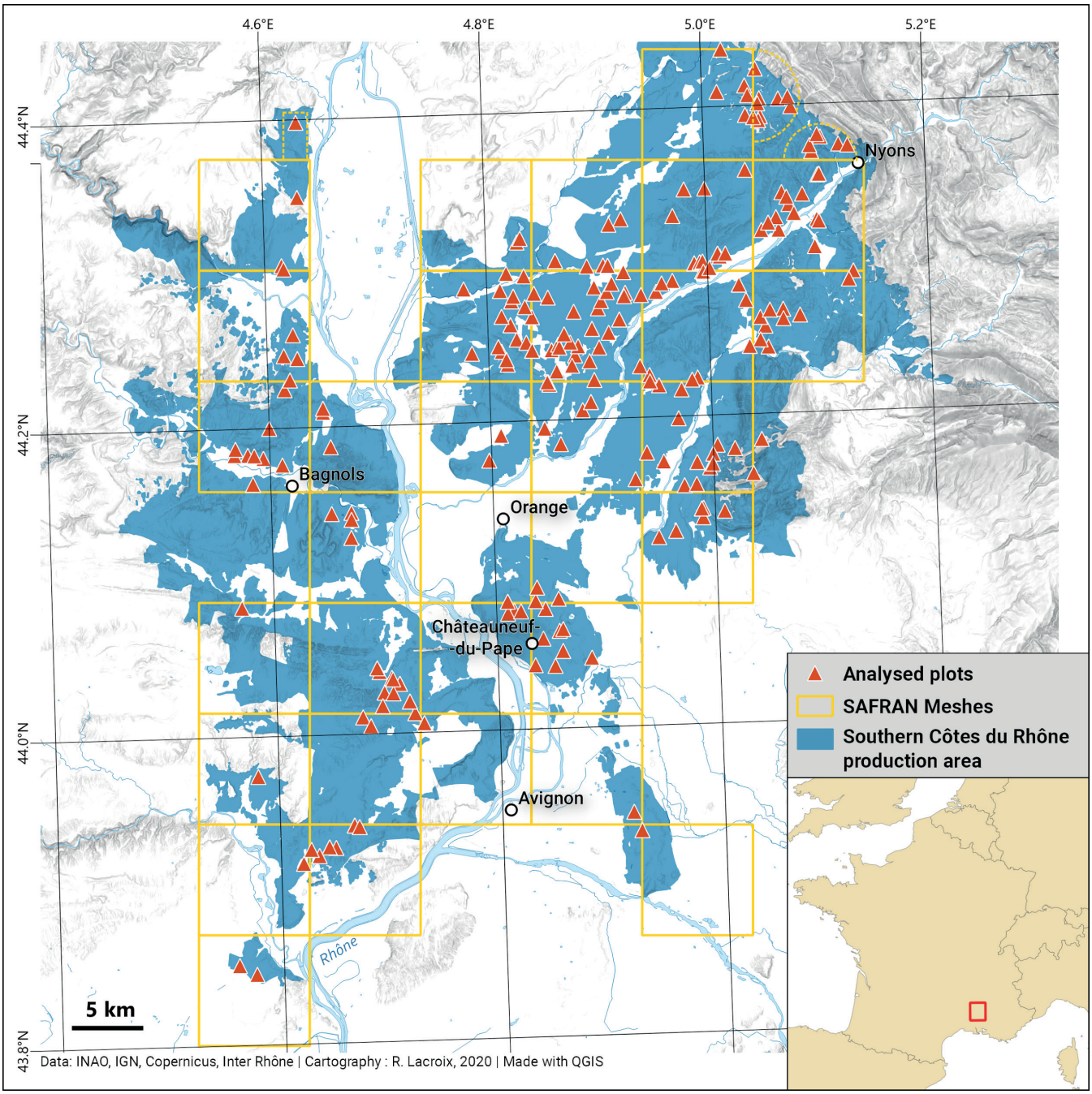


FIGURE 1. Distribution of Grenache sampled plots in the southern Rhône valley vineyard.

can serve as a basis for understanding recent changes observed in the vineyard.

This study contributes to the analysis of climate change impacts on viticulture in a major Mediterranean vineyard by investigating changes in the regional climate during the vine-growing seasons of the 1969–2020 period and determining its effect on berry composition. This first analysis of the open database aimed to confirm some results already obtained in previous studies. The data could contribute to improving our understanding of the influence of climate change on the changes in such Mediterranean vineyards, specifically the Rhone Valley vineyard.

MATERIALS AND METHODS

1. Berry composition database

The database can be freely downloaded via this permanent link: https://data.inrae.fr/dataset.xhtml?persistentId=doi:10.15454/H8VJCM

1.1. Plot network

A maturity network was set up in 1969 and has evolved to cover the whole Rhône Valley area to determine the maturity dynamics of different traditional grape varieties, such as Grenache, Syrah and Carignan.

The study focused on the Southern Rhône valley and the Grenache (the main grape variety). Figure 1 shows the distribution of the sampled plots of Grenache in the Southern Côtes du Rhône production area. In the database, this area is represented by continuous data obtained from 15 to 20 plots before 1982 and around 90 plots from 1982 to 2020 (see Supplementary Material, Figure 1B SM: Number of plots sampled per year). The 15 to 20 plots of the first decade remained in the network for at least 30 years, which is long enough to assess any changes to grape maturity parameters using a common dataset. The impact of this increase in the number of plots on the dataset was evaluated (data not shown) and no significant changes were observed. Moreover, for the 1969–1982 period, inter-annual variability was mainly observed, as well as a lower variability coefficient of the variables measured within the plots. To study the longer period, it was decided to retain the whole dataset.

1.2. Grape analysis database

The sampling routine started around two weeks after véraison (BBCH 85) and took place every Monday until the grapes were harvested by the winegrowers. This methodology allowed us to follow the different dynamics of various quality and yield variables during the whole ripening period. Thus, the date that the last sample was taken in a given plot during the season matched the harvest day with a maximum error of 6 days. Hereafter, for a given plot, this last sample analysis will be referred to as the harvest grape maturity. In each plot, a single row was identified for sampling from the first sample to harvest, and a 200-berry sample was collected from both sides of the canopy. This study focused on maturity parameters for which contiguous data series were available from 1969 onwards: total acidity, pH, potential alcohol and 200-berry weight.

First, the 200-berry sample was weighed (expressed in grams), then it was crushed and the must analysed. Potential alcohol was expressed by converting sugar concentration (g/L) to potential alcoholic strength by volume in the finished wine (% vol.). The conversion coefficient used was 16.83 g/L sugar = 1% of alcohol by volume in the finished wine. From 1969 to the end of the 1990s, this maturity parameter was measured by refractometry. We took into account that before 2004, the conversion coefficient commonly used by the laboratory was 17.5 g/L of sugar to make 1 % alcohol by volume in the case of red grapes. All potential alcohol data were rearranged to be on the same contiguous 16.83g/L basis. Nowadays this parameter is analysed by calibrated FTIR (Fourier Transform InfraRed spectroscopy).

Total acidity was expressed as the equivalent of g. of sulphuric acid per litre of must or wine (g H_2SO_4/L). From 1969 to the end of the 1990s, these values were measured by titration with NaOH 0,1N; once again, this parameter is now analysed by FTIR. From 1969 to the end of the 1990s, pH was measured using a pH electrode. Nowadays this parameter is analysed by FTIR.

The final Grenache variety database contains 16,058 records. For the study, the following values were used separately:

- The harvest values: from each of the reference plots, the values of the last sample were used for the berry composition data at harvest (3689 records). The harvest date is considered to be an unclear phenological stage, depending on the style of wine wanted by the winemaker and other events that can occur throughout the harvest period, which will influence final berry composition data.
- The September 1st values: for each plot, values of the sample closest to September 1st were used (3681 records). Harvesting before this date is very rare (more than 95 % of plots are harvested after September 1st); it is a fixed and symbolic date that allows any changes to maturity in the long term to be assessed without taking into account the effects of each winegrower's management of grape maturity.

Data distribution per year is available in Figure 1A SM.

2. Climate data

In the present study, past high-resolution climate data from the SAFRAN Météo France database was used to consider the spatial variability of the grape database (Quintana-Segui *et al.,* 2008; Vidal *et al.,* 2010). The SAFRAN Météo France database is used in France to spatially characterise the impacts of climate change (Vidal *et al.,* 2010) and has already been used in previous grapevine studies (Marjou and García de Cortázar-Atauri, 2019; Sgubin *et al.,* 2018). Spatialised reanalysed data regarding several climate variables on a scale of 8 × 8 km (64 km²) were thus obtained for the period 1968–2020: minimum, average and maximum temperatures (°C), rainfall (mm), radiation (J/cm²), wind (m/s) and relative humidity (%). Each plot was linked to the overlapping mesh data, except for when the mesh was located in an elevated region, in which case the plot was linked to the closest mesh (see Figure 1). The study area covers 32 meshes (grid cells). However, the number of cells over the years was not constant, as the number of analysed plots increased over time. For example, the network covered 7 cells in the 1970s and more than 20 after 1980.

3. Grapevine phenological stages

Six main phenological stages were considered to assess the grapevine growing cycle: budburst, flowering, fruit set, lag-phase end, véraison and harvest. The dates of these stages (expressed as day of the year, DOY) were calculated using different phenological process-based models calibrated according to the literature on the Grenache cultivar and using the average temperature data from each SAFRAN grid cell of the studied area.

Simple models were chosen from the literature, which can be applied under very different conditions and easily computed daily by its users (Parker *et al.,* 2011; Parker *et al.,* 2013; Parker *et al.,* 2020). These simple models are consistent enough to be confident about the results of the simulated phenology stages when compared with more complex models (Morales-Castilla *et al.,* 2020; García de Cortázar-Atauri *et al.,* 2009a) (a comparison of these models is available in Figure 2SM).

TABLE 1. Climate indicators and the phenological phases for which they were calculated.

Indicator	Variable	Description	Phenological phases							
			Bud-Flow	Flow-Set	Set-Lag	Lag-Ver	Ver-Harv	Flo-Ver	Set-Ver	Flo-Harv
mint	Tmin	Average Tmin for each period	X	X	X	X	X	X	X	X
maxt	Tmax	Average Tmax for each period	X	X	X	X	X	X	X	X
meant	Tmean	Average Tmean for each period	X	X	X	X	X	X	X	X
ranget	Tmin, Tmax	Average Thermal amplitude for each period	X	X	X	X	X	X	X	X
sumsorad	Radiation	Cumulated daily radiation	X	X	X	X	X	X	X	X
sumwd	ETP, Rainfall	Sum of water deficit (ETP - Rainfall)	X	X	X	X	X	X	X	X
rainsum	Rainfall	Rain cumulation	X	X	X	X	X	X	X	X
raifreq	Rainfall	Frequency (%) of rainy days within the period (Daily Rainfall > 0.0mm)	X	X	X	X	X	X	X	X
phalen	Dates	Phase length (number of days)	X	X	X	X	X	X	X	X
cdaystmin	Tmin	Number of cold days (tmin < 0.0°C)	X	X						
cfreqtmin	Tmin	Frequency (%) of cold days within the period (tmin < 0.0°C)	X	X						
hwindfreq	Wind	Frequency (%) of days with high wind within the period (wind speed > 5.28 m/s)	X	X	X	X	X	X	X	X
wetfreq	RH	Frequency (%) of wet days within the period (RH > 60%)	X	X	X	X	X	X	X	X
hsdays	Tmax	Number of heat stress days (tmax > 35°C)		X	X	X	X	X	X	X
xhsdays	Tmax	Number of heat stress days (tmax > 40°C)		X	X	X	X	X	X	X
hsfreq	Tmax	Frequency of heat stress days (tmax > 35°C)		X	X	X	X	X	X	X

Bud-Flow = budburst to flowering; Flow-Set = flowering to fruit set; Set-Lag = fruit set to end of lag-phase of herbaceous berry growth (phase II); Lag-Ver = end of lag-phase of herbaceous berry growth to véraison; Ver-Harv = véraison to harvest (maturation phase); harvest = véraison + 35 days; Flo-Ver = flowering to véraison; Set-Ver = fruit set to véraison; Flo-Harv = flowering to harvest (harvest = véraison + 35 days).

All the climate variables were obtained from the SAFRAN MétéoFrance Database where: Tmin is the minimal daily temperature (°C); Tmax is the maximal daily temperature (°C); Tmean is mean daily temperature (°C); Radiation is the daily radiation cumulation (J/cm²); Rainfall is daily rainfall (mm); ETP is daily evapotranspiration (mm) calculated with the FAO formula (Allen *et al.*, 1998). Wind is the mean daily wind (m/s); RH is the daily relative humidity (%). Dates are the day of the year of the simulated phenological stage (DOY); Empty cells = indicators were not calculated because they were not relevant. All the indicators were calculated using the GETARI software (García de Cortázar-Atauri and Maury, 2019) to compute a large number of indicators during a specific phase defined by the user and using different daily or hourly climatic variables from a single point (here from each single SAFRAN grid).

Figure 3SM summarises the development stages and the models used in this study.

The budburst date (BBCH 07 - EL 05) was calculated using a version of the Growing Degree Days model which had been tested by García de Cortázar-Atauri *et al.* (2009a) on the Grenache cultivar. This model considers that budburst is reached when the sum of the degree days above 5 °C as from January 1st (in the Northern Hemisphere) reaches 321 °C.d. The BRIN model (which takes into account the dormancy period) was not considered for use, because it was not expected to have had a dormancy delay over the past 50 years (as described in García de Cortázar-Atauri *et al.,* 2009a). The flowering (BBCH 65 - EL 23) and véraison (BBCH 85 - EL 35) dates for Grenache were calculated using the GFV model (Parker *et al.,* 2011; Parker *et al.,* 2013). These phenological stages are reached when the sum of degree days above 0 °C as from the 60th day of the year (in the Northern Hemisphere) reaches 1269 °C.d. and 2750 °C.d. respectively.

The fruit set (BBCH 71 - EL 27) and end of lag-phase (BBCH 77 - EL 32) dates were estimated using a Growing Degree Days model based on the average temperature above 10 °C after the flowering dates. The end of the lag phase was observed when the end of the herbaceous berries growth curve was reached (or phase II) (see García de Cortázar-Atauri *et al.,* 2009b). The cumulated degree days for each stage of Grenache have been proposed by García de Cortázar-Atauri (2006) for fruit-set (133 °C.d.) and by García de Cortázar-Atauri *et al.* (2009b) and Ojeda *et al.* (1999) for the end of the lag-phase (600 °C.d). Finally, and as previously explained, a harvest date is related more to the style of wine desired by the winegrower than to a precise phenological stage (García de Cortázar-Atauri *et al.,* 2010; Morales-Castilla *et al.,* 2020). To define a harvest date from the data, it was first estimated for each plot in the maturity database belonging to a certain SAFRAN grid cell; this was done by calculating the geometric mean of the last analysis date of each year. The harvest date was thereby calculated to occur on average about 35 days after véraison, which is consistent with the literature for our grape variety and our region (Yiou *et al.,* 2012; García de Cortázar-Atauri *et al.,* 2017; Morales-Castilla *et al.,* 2020). Therefore, it was decided to apply the calculation of 35 days after véraison for the harvest date.

To check that the processed-based models used in this study are relevant in our region and fit the inter-annual variability, the modelled dates and observed dates of main phenological stages were compared, as shown in Figure 4SM.

4. Ecoclimatic indicators

To describe the impact of climate on Grenache maturity descriptors at harvest (total acidity, pH, 200-berry weight and potential alcohol), a large set of climatic indicators were identified and calculated during different phenological periods according to the literature and expertise. These indicators were calculated using different climate variables from the SAFRAN database: maximal, minimal, and mean temperature, rainfall, radiation, wind speed and humidity. To determine the impact of interannual climate changes on phenology (Caubel *et al.,* 2015), six main stages were calculated using the previous model for splitting the grapevine development into eight different phases (see Table 1).

The dates of the stages were calculated using climate data specific to each grid cell and assigned to each plot depending on its location. Table 1 shows the indicators and the phases for which they were calculated (with an X).

Lastly, because pH is highly dependent on the total acidity values, and to avoid obtaining redundant results, this variable was omitted from the following analysis.

5. Statistical analysis

Each climate indicator was aggregated according to phenological period and SAFRAN grid cells and entered into GETARI software to calculate the list of indicators described in Table 1. Thus, for each plot and year, it was possible to match the maturity data and the phenological climatic indicators of the cell in which each plot was located.

R Statistics Environment (R Core Team, 2020) was used for all statistical analyses and graphs, with tidyverse, agricolae, corrplot, gt and ggpubr packages. Linear regressions were performed for the interannual changes in phenological stages, maturity parameters, climatic indicators, and for the relationships between them. These interannual regressions are often associated with box plots to show in a more condensed format the distribution of parameter values over the vineyard plots/SAFRAN cells. A number of annual trends can be observed in the summary table of regressions (Table 1SM), where standard deviation and significance are also shown.

Matrices of Pearson's correlation coefficients of the ecoclimatic indicators at different phenological stages were computed to examine the relationships between climate and grapevine profile at harvest (Table 2, Figure 10SM); the values to be correlated were centred.

To show the trend for the number of relationships, the values were aggregated according to decade. To show the non-linear growth of maturity indicators during the maturation process, loess regressions were also used on some graphs.

RESULTS

Here we first describe the changes to the different maturity parameters measured at different times of maturation over the past 50 years. Then we evaluate the impact of climate on phenology and maturity using different calculated indicators. As previously mentioned, because the results obtained for pH are very similar to those obtained for total acidity, only total acidity is taken into account. The year 1970 was excluded from this study due to a lack of data.

1. Dynamics of quality and yield compounds over the past 50 years (1969-2020)

1.1. Trends observed at harvest date

The results of the analysis of Grenache berries at harvest date show a significant decrease in total acidity and berry weight (p-value <= 0.001), and a significant increase in potential alcohol (p-value <= 0.001) (Figure 2); further information can be found in Figure 5SM (Multiple comparison of years by means of Least Significant Difference and grouping of years). It was also observed that the variations and data distribution are not constant over the fifty years, making it possible to identify exceptional vintage effects; for example, exceptionally high acidity values in 1984 (with high variability), very low acidity values in 2018 (lower median over the studied period) and extremely low berry weights and high potential alcohol in 2019. The pH regression is shown in Figure 6SM.

The linear regressions (represented by red lines in Figure 2 and summarised in Table 1SM) show an overall decrease of 1.3 g/L in acid concentration at harvest during the 1969–2020 period (i.e., -0.026 g/L per year) and an increase of 2.7 %vol.

in alcohol (i.e., +0.052 %vol. per year). Moreover, in terms of extreme values for both variables, in the last few years the acidity values were very low (some of around 2 g/L) and potential alcohol very high (up to nearly 18 %vol.). Regarding the 200-berry weight, the overall decrease is about 88 g in the 1969–2020 period (i.e., -1.72 g per year).

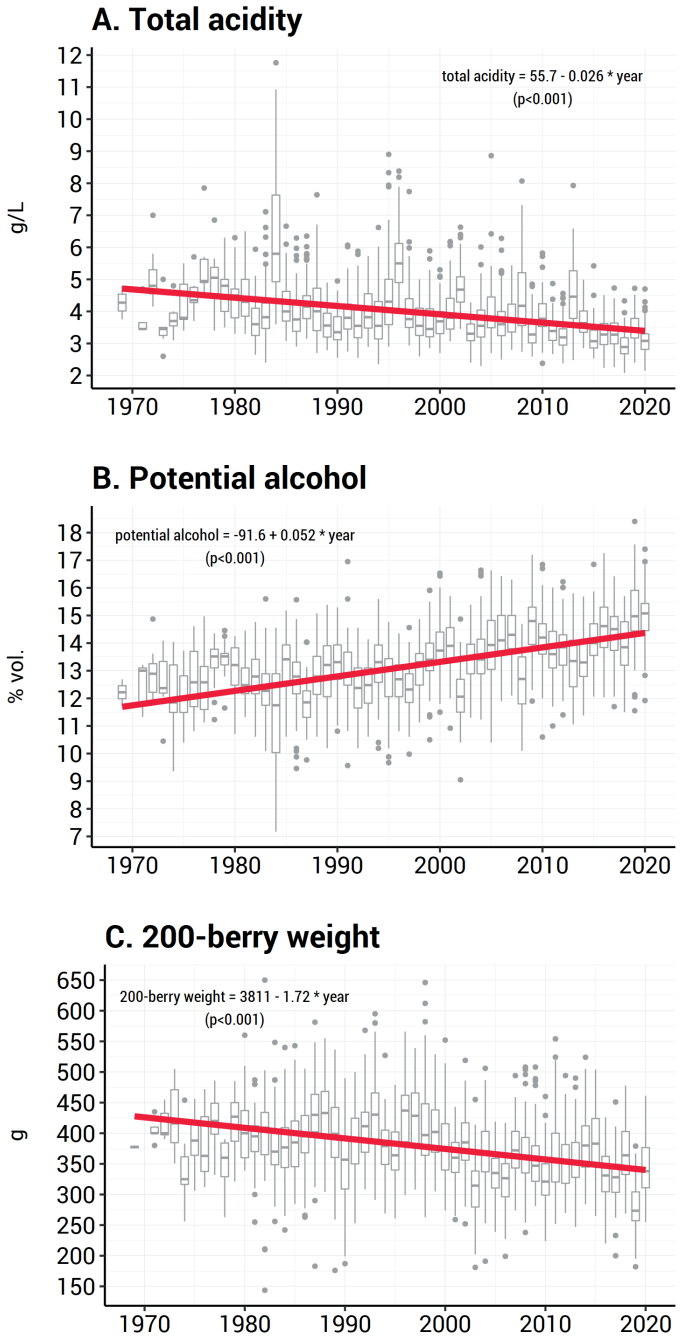


FIGURE 2. Overview of Grenache maturity at harvest in the southern Rhône valley from 1969 to 2020.

A) Total acidity (g/l); B) Potential alcohol (% vol.); C) 200-berry weight (g). Box-plots show the distribution of the data: the line in the middle of the box is the median value of the dataset, the box delimits 25 and 75 % quantiles. Grey dots are outlier values.

Red lines represent linear regressions applied to the whole maturity-at-harvest dataset.

1.2. Analysis of the interannual variations of the maturity dynamics

Figure 3 shows the changes in maturity parameters per day-of-year, grouped into decades in graphs A, B and C (represented by the local regression), or per year for graphs D, E and F. Three recent and noticeable vintages are represented in Figures 3A, B and C: i) the year 2003, which was characterised by an important heatwave at véraison, ii) the year 2018, which was characterised by a very wet spring, and iii) the year 2019, which was characterised by a very early heatwave (temperatures above 40 °C in June). The data represented in these figures can be analysed in different ways. From the decade curves, it is possible to assess the decadal development of maturity dynamics in terms of day of year (i.e., the variation on the X-axis). Moreover, the date (day of the year) of reaching a given value of acidity, alcohol or berry weight can be seen to be earlier and earlier; for example, 5 g/L of total acidity was reached between 7 and 15 September in the 1970s and 1980s, and between 15 and 22 August in the 2010s.

On the other hand, an analysis of the data of each variable on a specific day of the year (variation on Y-axis) reveals changes per decade: on a given day, acidity decreases, potential alcohol increases and berry weight increases during the first three decades (1970s to 1990s) and then drastically decreases during the last 2 decades (since 2000s).

As a result, today's potential alcohol at the beginning of the maturation analysis was generally found to be higher than the values at harvest in the 1970s. Records were reached in recent years, such as in 2019 and 2020 when a median value 15 %vol. was reached on 15 September, a value that was not even reached during the 1970s and 1980s. Moreover, the 200-berry weight increased slightly during the first weeks of the maturation process and then stayed quite constant during the last few weeks. Nevertheless, there is a significant gap before and after the 1990s: the weight of 200 berries at harvest was often around 380–400 g before the 1990s–2000s, yet in the last two decades it was around 360 g. The 2019 vintage differs dramatically from the others, with extremely low berry weight (final 200-berry weight at harvest was around 280 g).

A sampling artefact is visible on the smoothed curves of Figure 3A, B and C, especially on the acidity and alcohol graphs, with a rise and a fall respectively in the values at the end of the season. This is because at the end of the maturation sampling season only the later ripening plots remain.

2. Impact of climate on grapevine development stages and maturity profile

2.1. Changes in grapevine phenology

Due to the lack of phenological observations on the different study plots, the main grapevine development stages were calculated using the SAFRAN temperature data for each grid cell. These simulations show that, over the last 50 years, the initial stages (budburst, flowering) take place 10 to 15 days earlier, increasing to 15 to 20 days for the final stages (end of lag period, véraison and harvest).

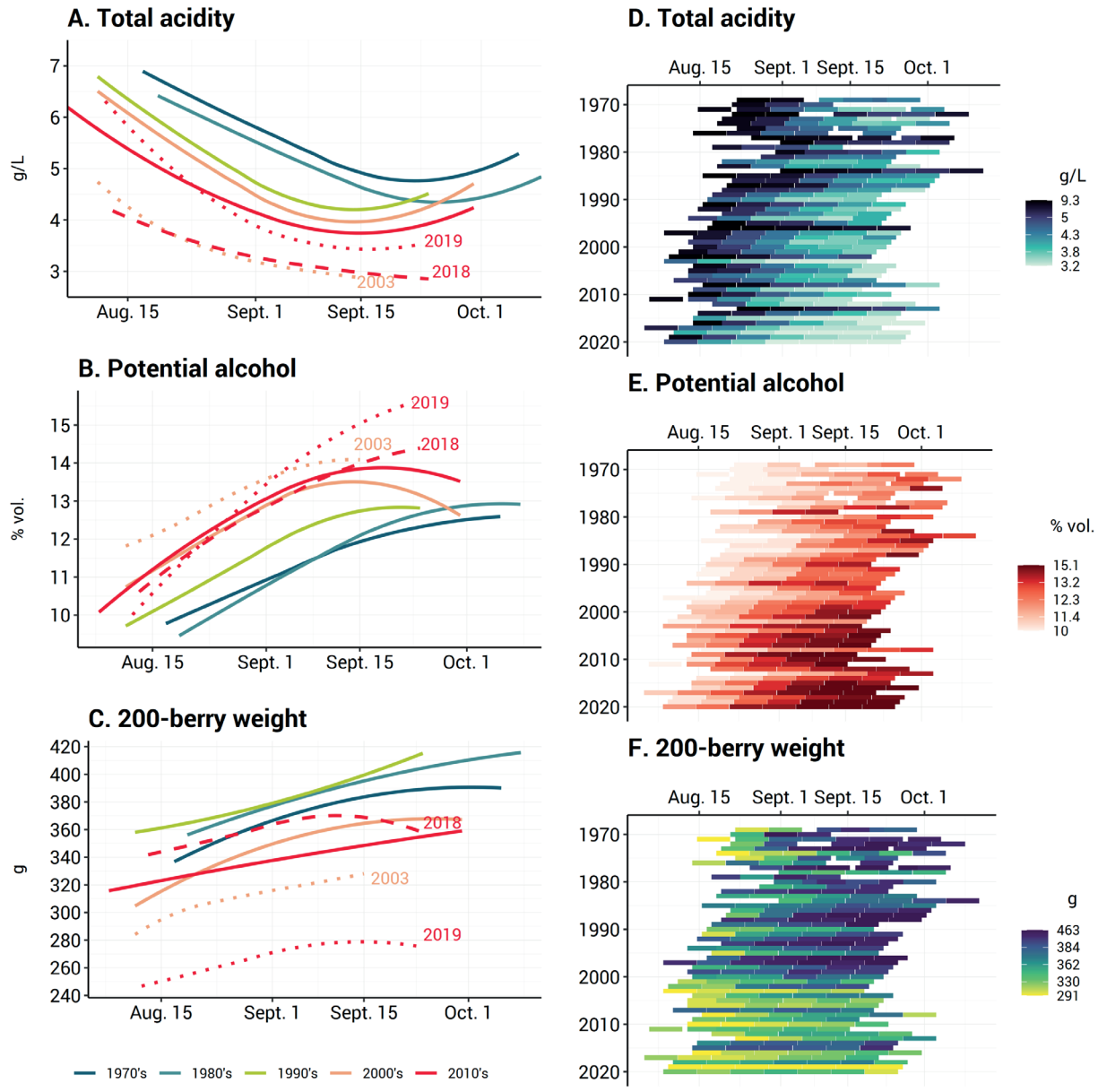


FIGURE 3. Decadal and interannual variations of the maturity dynamics.

A) Smoothed curve of the dynamics of the Total acidity (g/l) per decade and single years 2003, 2018, 2019; B) Smoothed curve of the dynamics of the Potential Alcohol (% vol.) per decade and single years 2003, 2018, 2019; C) Smoothed curve of the dynamics of the 200-berry weight (g) per decade and single years 2003, 2018, 2019; D) Dynamics of the Total acidity per year; E) Dynamics of the Potential Alcohol per year; F) Dynamics of the 200-berry weight (g) per year.

On A, B, C, curves are calculated applying local regressions.

On D, E, F, each tile is a grape sampling week, filled colour is the geometric mean for all samples of the week.

For further information, phenology statistics and regression values are available in Table 1SM. As the vineyard plots in the database are located on several grid cells, there is variability in the estimated phenological stages (shaded areas of each stage curve). In Figure 4, a decrease in this variability can be observed over the last few decades (2000s and after) (see complementary information in Figure 7SM). This decrease in grapevine phenology variability results from the homogenisation of the climate conditions in the different vineyard plots of the maturity network of the study wine region (Figure 8SM).

Figure 9SM shows the daily mean temperatures per decade in the city of Orange (data from Climatik database, AgroClim INRAE) and the average calculated phenological stages, thus providing an overview of their changes in parallel with changes to the temperature conditions in the Rhône Valley.

2.2. Relationships between grape maturity and agro-climatic indicators

Table 2 shows the results of the correlation analyses carried out using maturity parameters at harvest and climate indicators per phase. Only the short phases were kept because

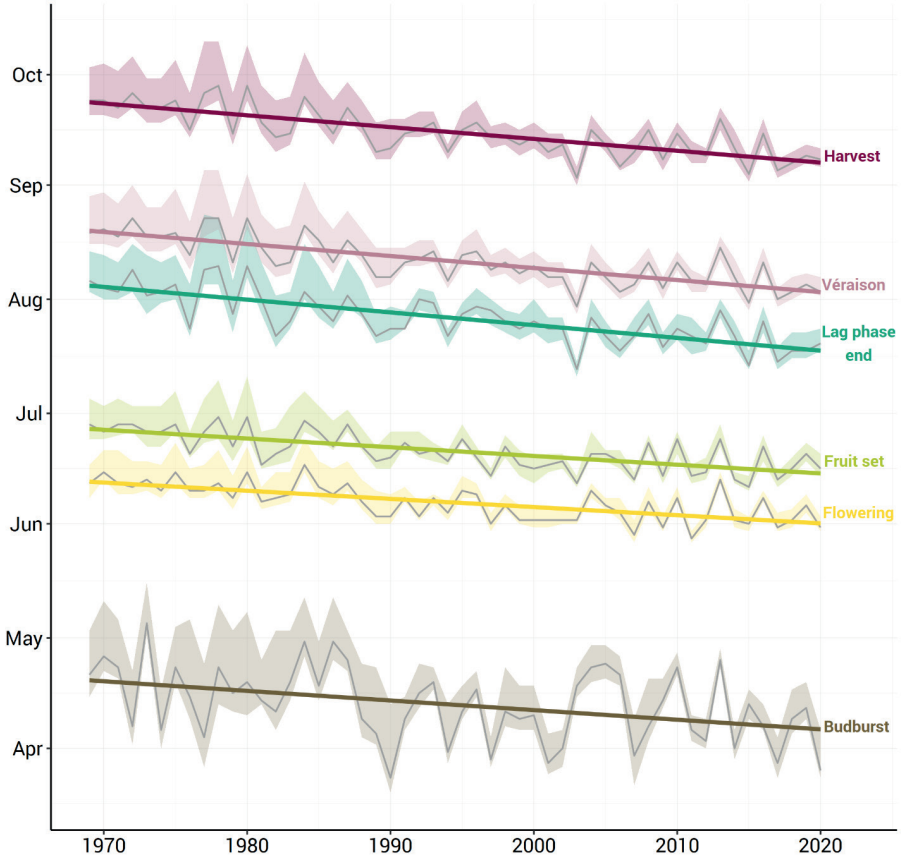


FIGURE 4. Changes in simulated phenological stages.

Bold lines are linear regressions for phenological stages calculated for each SAFRAN grid cell. The shaded area represents the interval between the 1st and the 9th decile. The grey line represents the median value of all the grid cells (see regression equations in Table 1SM).

long phases such as Flowering-Véraison or Flowering-Harvest were giving lower absolute correlation values (data not shown). The results confirm that the climate conditions during the final phenological phases have a direct effect on quality and yield.

The highest positive and negative correlations between climate indicators and the three maturity parameters *Total Acidity*, *Potential alcohol* and *200-berry weight* were then analysed (boxed cells in Table 2.). Given that the correlations related to pH are quite the opposite of those of total acidity, no further details are given here.

Most of the climate indicators show in-between correlations as can be seen in Figure 10SM showing the correlations between climatic indicators at different phenological phases.

2.2.1. Total Acidity

Total acidity correlates with climate indicators the most significantly during the Véraison-Harvest phase, the Lag-Véraison phase and more marginally during the *Bud-Flow* phase. Temperatures after véraison appear to be highly correlated with the harvest value, as well as with solar radiation, water deficit and humidity.

The highest negative correlation in terms of the total acidity grape parameter is observed during the Véraison-Harvest phase with the climate indicator *Mean temperature*. Figure 5 shows the crossed changes to these two parameters. The increase in average temperatures during the Véraison-Harvest phase (Figure 5B) can be seen in parallel with the decrease in total acidity at harvest (Figure 5A). The higher the mean temperature during this phase, the lower the total acidity at harvest. The correlation and its graphical transcription with a linear regression (Figure 5C) show its limits for the year 2003, which, due to its extreme nature, indicates that the relationship is not exactly linear and physiological issues can occur in very high ripening temperatures.

The highest positive correlation for the total acidity grape parameter was with the *Water deficit* climate indicator during the Budburst-Flowering phase. Although the water deficit during this period has decreased significantly over the last few years (Figure 6), it is highly variable from year to year and leads to an interesting correlation: the more the vine is water-stressed during the early phases, the lower the acidity at harvest.

2.2.2. Potential alcohol

Water deficit and radiation are correlated with potential alcohol as early as the Budburst-Flowering phase. After fruit set, temperatures become the main climate factor to have an impact on alcohol at harvest, overtaking water deficit.

TABLE 2. Pearson's correlation coefficients between maturity parameters at harvest and climate indicators per phase.

		Correlations per maturity parameter and per phenological pediod by climate indicator														
		Total acidity					**Potential alcohol**					**200-berry weight**				
Type	Indicator	Bud-Flow	Flow-Set	Set-Lag	Lag-Ver	Ver-Harv	Bud-Flow	Flow-Set	Set-Lag	Lag-Ver	Ver-Harv	Bud-Flow	Flow-Set	Set-Lag	Lag-Ver	Ver-Harv
Heat	**hsfreq**		0,01	-0,06	-0,13	-0,23		0,03	0,11	0,10	0,17		-0,03	-0,21	-0,19	-0,18
Heat	**hsdays**		0,01	-0,06	-0,13	-0,23		0,03	0,09	0,11	0,17		-0,02	-0,20	-0,21	-0,18
Heat	**xhsdays**			-0,04	-0,02	-0,03			0,14	-0,01	-0,01			-0,18	-0,02	-0,08
Humidity	**wetfreq**	0,16	0,03	0,21	**0,31**	**0,35**	-0,16	-0,13	**-0,34**	**-0,36**	**-0,47**	0,16	0,16	**0,29**	**0,28**	**0,39**
Phase	**phalen**	-0,16	-0,06	**0,25**	0,06	0,01	0,13	-0,02	**-0,26**	0,07	0,00	-0,04	0,04	**0,36**	-0,22	0,02
Radiation	**sumsorad**	**-0,28**	0,07	0,10	-0,27	**-0,47**	**0,29**	-0,04	-0,02	**0,32**	**0,51**	-0,16	0,02	0,18	**-0,32**	**-0,26**
Rainfall	**raifreq**	0,24	-0,13	0,08	0,20	**0,28**	-0,13	0,11	-0,14	-0,09	**-0,32**	0,10	0,03	**0,25**	0,12	0,09
Thermal conditions	**rainsum**	0,24	-0,15	0,17	0,14	0,20	-0,15	0,08	-0,18	-0,14	-0,30	0,09	-0,02	0,16	0,09	0,11
Thermal conditions	**meant**	-0,16	0,06	-0,25	**-0,40**	**-0,60**	0,14	0,02	**0,27**	**0,27**	**0,43**	-0,07	-0,03	**-0,38**	-0,22	**-0,27**
Thermal conditions	**maxt**	-0,20	0,06	-0,14	**-0,30**	**-0,56**	0,16	0,03	0,20	0,17	**0,43**	-0,04	-0,04	**-0,38**	-0,19	**-0,27**
Thermal conditions	**mint**	-0,13	0,00	**-0,32**	**-0,41**	**-0,55**	0,12	0,02	**0,30**	**0,31**	**0,38**	-0,02	-0,04	**-0,33**	-0,11	-0,24
Thermal conditions	**ranget**	-0,16	0,08	0,13	0,03	-0,19	0,10	0,02	-0,01	-0,10	0,20	0,04	-0,03	-0,09	0,08	-0,03
Thermal conditions	**cdaystmin**	-0,04					0,09					-0,01				
Thermal conditions	**cfreqtmin**	-0,04					0,08					-0,01				
Water deficit	**sumwd**	**0,36**	-0,12	0,21	**0,29**	**0,35**	**-0,28**	0,04	**-0,25**	**-0,30**	**-0,45**	0,17	0,07	0,25	**0,27**	0,20
Wind	**hwindfreq**	-0,21	0,01	-0,14	-0,14	-0,12	0,16	-0,01	0,08	0,10	0,18	-0,19	-0,10	-0,07	-0,11	-0,14

All correlations p-values < 0.001

Highlighted table cells show highest correlation values (absolute value |x| > 0.25): positive correlations in orange and negative correlations in blue. The highest positive and negative correlation for each maturity parameter total acidity, potential alcohol and 200-berry weight is boxed. The empty cells mean that the correlations could not be calculated.

Note: Bud-Flow = budburst to flowering; Flow-Set = flowering to fruit set; Set-Lag = fruit set to lag-phrase end of herbaceous berries growth (phase II); Lag-Ver = lag-phase end of herbaceous berries growth to véraison; Ver-Harv = véraison to harvest.

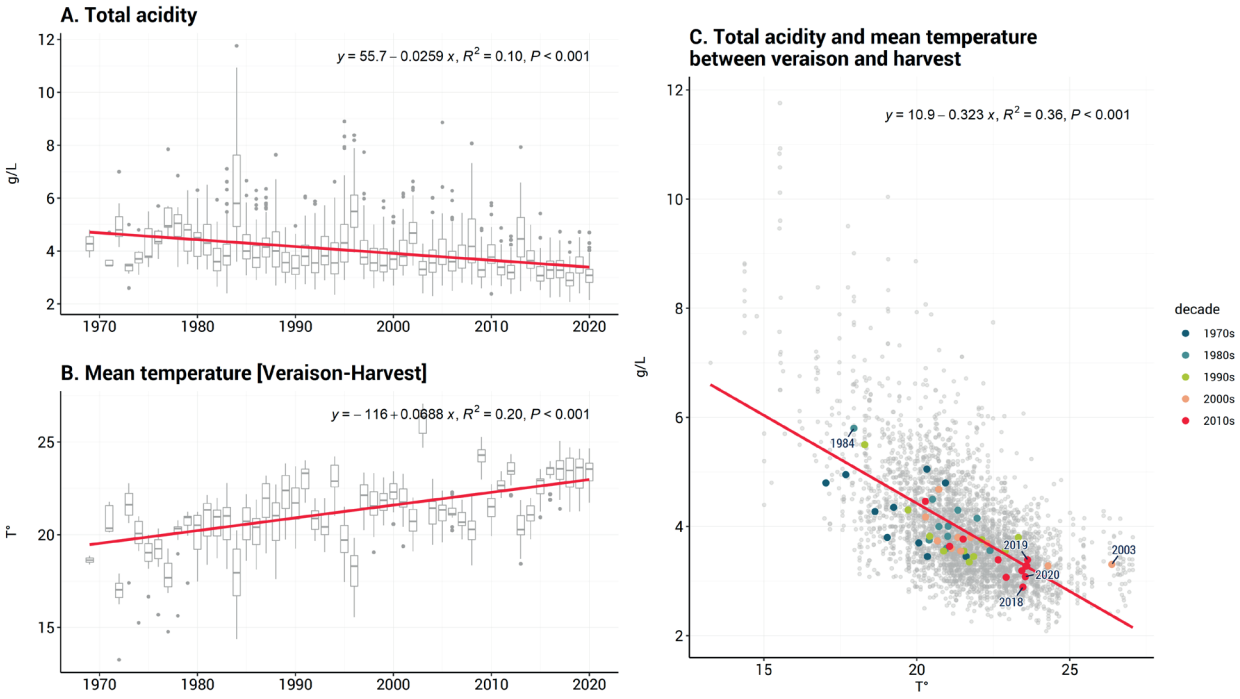


FIGURE 5. Relationship between total acidity and mean temperature during Véraison to Harvest phase.

A) Changes in total acidity (g/L); B) Changes in mean temperature during Véraison to Harvest phase; C) Relationship between total acidity and mean temperature during Véraison to Harvest phase. Red lines indicate linear regressions. In A) and B), the box plots show the distribution of the data: the line in the middle of the box represents the median value of the dataset; the box delimits 25 and 75 % quantiles, and the grey dots are outlier values. In C), the grey scatter plot in the background shows the raw data; the coloured dots represent median values of the maturity parameter [Total Acidity at harvest] per year, each colour representing a decade.

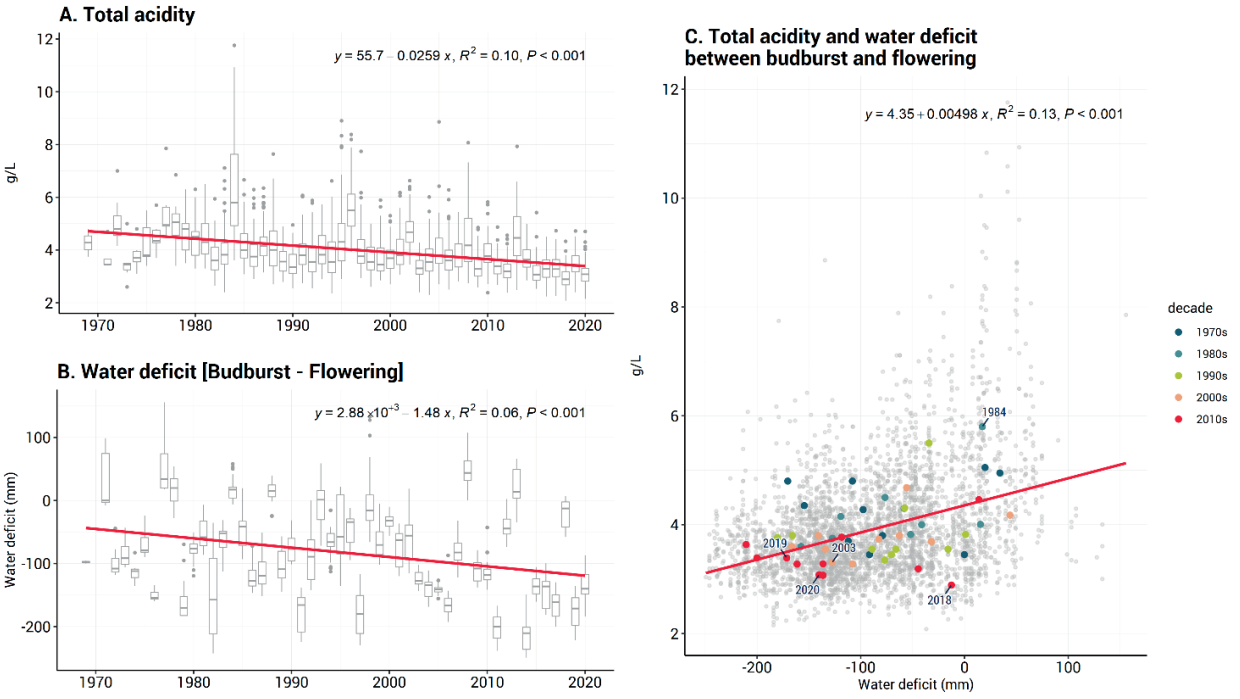


FIGURE 6. Relationship between total acidity and water deficit during the Budburst to Flowering phase.

A) Changes in total acidity (g/L); B) Changes in water deficit during the Budburst to Flowering phase; C) Relationship between total acidity and water deficit during the Budburst to Flowering phase.

Red lines represent the linear regressions. In A) and B), the box plots show the distribution of the data: the line in the middle of the box represents the median value of the dataset; the box delimits 25 and 75 % quantiles and the grey dots are outlier values. In C), the grey scatter plot in the background shows the raw data; the coloured dots represent median values of the maturity parameter [Total Acidity at harvest] per year, each dot representing a decade.

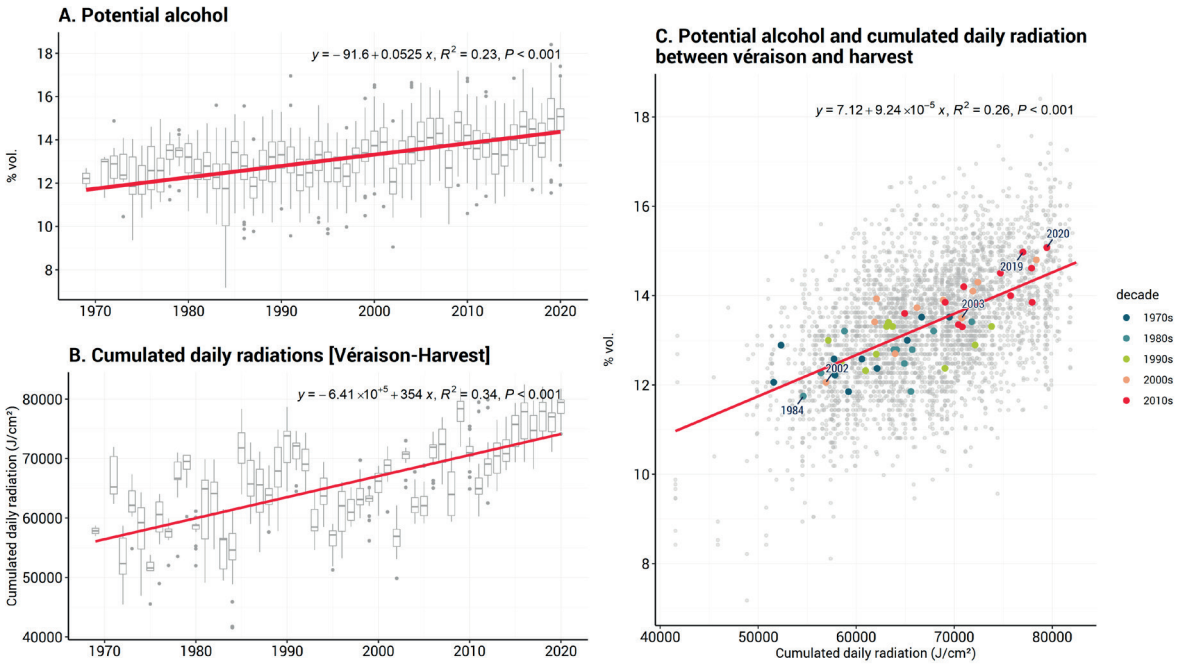


FIGURE 7. Relationship between potential alcohol and cumulated daily radiations during the Véraison to Harvest phase.

A) Changes in potential alcohol (% vol.); B) Changes in cumulated daily radiations during the Véraison to Harvest phase; C) Relationship between potential alcohol and cumulated daily radiations during the Véraison-Harvest phase.

Red lines represent the linear regressions. In A) and B), the box plots show the distribution of the data: the line in the middle of the box is the median value of the dataset; the box delimits 25 and 75 % quantiles and the grey dots are outlier values. In C), the grey scatter plot in the background shows the raw data. The dots represent the median values of the maturity parameter [Potential alcohol at harvest] per year, each colour representing a decade.

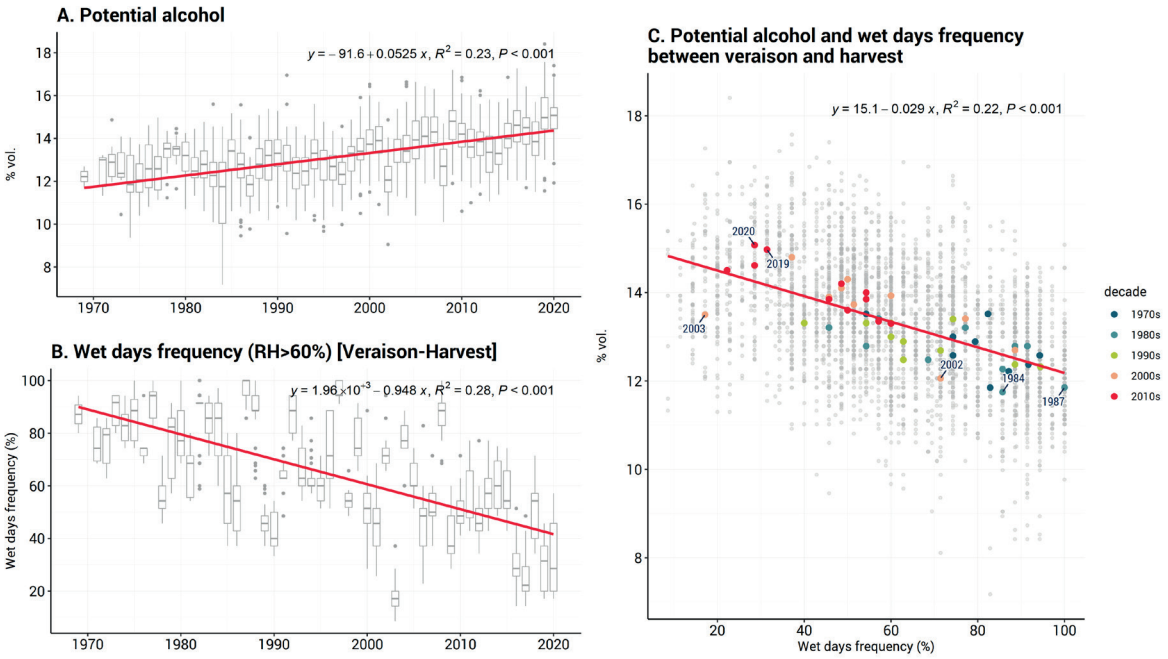


FIGURE 8. Relationship between potential alcohol and wet days frequency (RH > 60 %) during the Véraison to Harvest phase.

A) Changes in potential alcohol (% vol.); B) Changes in wet days frequency during Véraison-Harvest; C) Relationship between potential alcohol and wet days frequency during the Véraison-Harvest phase.

Red lines represent the linear regressions. In A) and B), the box plots show the distribution of the data: the line in the middle of the box is the median value of the dataset; the box delimits 25 and 75 % quantiles and the grey dots are outlier values. In C), the grey scatter plot in the background shows the raw data; The dots represent the median values of the maturity parameter [Potential alcohol at harvest] per year, each colour representing a decade.

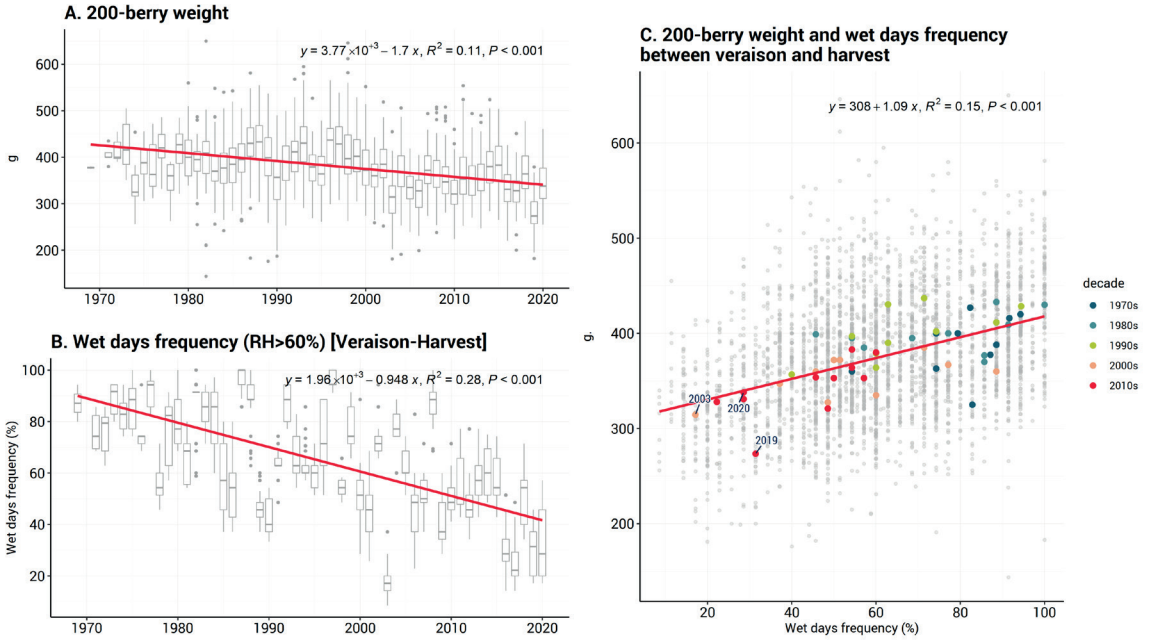


FIGURE 9. Relationship between 200-berry weight and wet days frequency (RH > 60 %) during the Véraison-Harvest phase.

A) Changes in 200-berry weight (g); B) Changes in number of wet days during the Véraison-Harvest phase; C) Relationship between 200-berry weight and number of wet days during the Véraison-Harvest phase.

Red lines represent the linear regressions. In A) and B), the box plots show the distribution of the data: the line in the middle of the box is the median value of the dataset; the box delimits 25 and 75 % quantiles and the grey dots are the outlier values. In C), the grey scatter plot in the background shows the raw data. The dots represent the median values of the maturity parameter [200-berry weight at harvest] per year, each colour representing a decade.

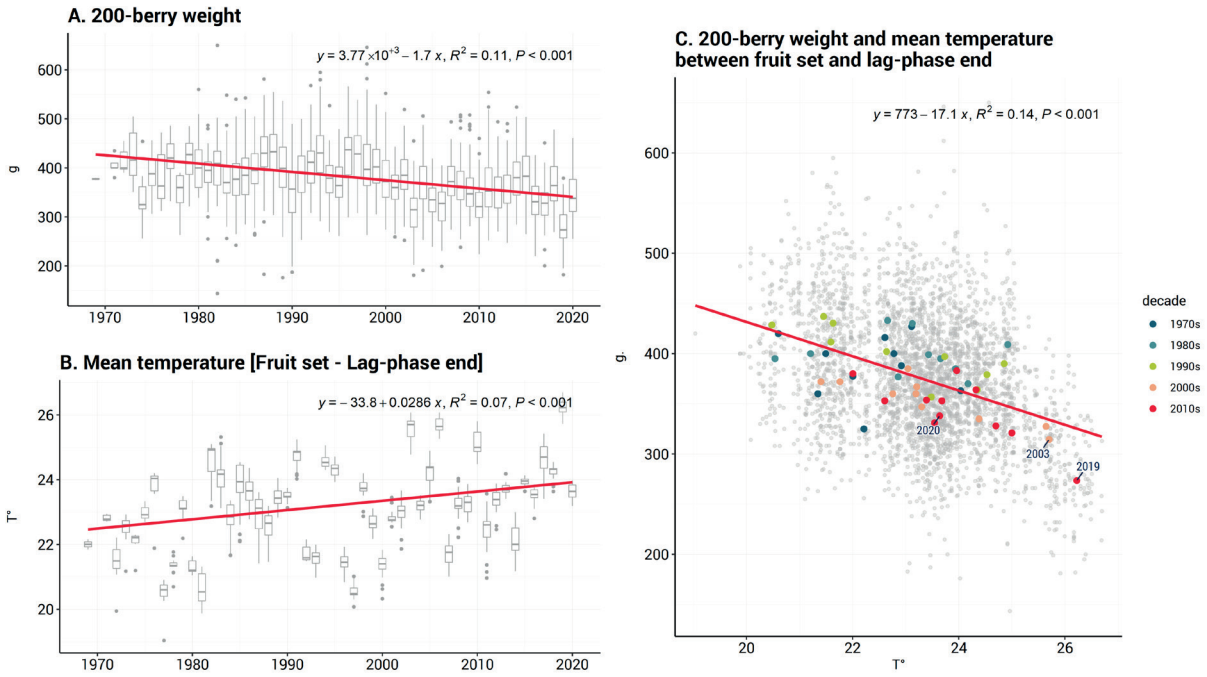


FIGURE 10. Relationship between 200-berry weight and mean temperature from Fruit-set to the end of the Lag-phase.

A) Changes in 200-berry weight (g); B) Changes in mean temperature during fruit-set to the end of the lag-phase; C) Relationship between 200-berry weight and mean temperature during fruit-set to the end of the lag-phase.

Red lines represent the linear regressions. In A) and B), the box plots show the distribution of the data: the line in the middle of the box is the median value of the dataset, the box delimits 25 and 75 % quantiles and grey dots are outlier values. In C), the grey scatter plot in the background shows the raw data. Bold points are figuring median values of the maturity parameter [200-berry weight at harvest] per year, coloured by decades.

Correlations with these climate indicators are stronger after véraison, but a relationship with the previous herbaceous stages is still observed.

The highest positive correlation for potential alcohol at harvest is observed during the Véraison-Harvest phase with the *Cumulated daily radiations* climate indicator, as shown in Figure 7. There is a clear increase in the sum of daily radiations during the Véraison-Harvest period; there is thus a significant correlation between the high values of the sum of solar radiation during the Véraison-Harvest period and the high values of potential alcohol at harvest.

The highest negative correlation for potential alcohol at harvest was observed with the *wet days frequency (Relative Humidity > 60 %)* climate indicator during the Véraison-Harvest phase. There is a clear drop in wet days frequency during the ripening phase (Figure 8), which can also be explained by the shift in ripening to warmer and dryer summer periods. The results show that the less wet this period is, the higher the potential alcohol will be.

2.2.3. 200-berry weight

Berry weight seems to be mainly driven by the climate of the Fruit Set-Lag phase. Some parameters, like humidity, are correlated with berry weight at harvest during all berry development and ripening phases; others, like temperature, primarily affect berry weight during the Fruit Set-Lag and Véraison-Harvest phases. Temperature has a negative correlation with berry weight, with high temperatures causing a shortening of the growing phase (this phase can be established from the sum of degree days).

The highest positive correlation for the 200-berry weight was observed with the *wet days frequency (Relative Humidity > 60 %)* climate indicator during the Véraison-Harvest phase. Figure 9 shows the values for these two parameters; the decrease in wet days during the Véraison-Harvest phase can be seen to be in parallel with the decrease in berry weight. The higher the wet day frequency during this phase, the higher the berry weight at harvest.

The highest negative correlation for 200-berry weight was observed for the climate indicator *Mean temperature* during the Fruit Set-Lag phase. Figure 10 shows that the average temperature during this phase increased considerably. The length of the Fruit Set-Lag phase is linked to temperature, which results in a shorter berry growth phase, and therefore a decrease in berry weight at harvest; this was observed in 2019, when a strong heatwave occurred during the Fruit Set-Lag phase, resulting in the smallest berries to have ever been observed in the last 50 years.

3. Comparing maturity values at harvest and on September 1st

By comparing variations in maturity values at harvest on the one hand, and on September 1st on the other, it is possible to determine how much of grape maturity is due to climate change (value on September 1st) and how much reflects the winegrower's touch (value at harvest). September 1st is the 244th day of the year (245th in bissextile years); it was chosen because values are available for all 50 vintages, whether it be an early or late-ripening year.

Figure 11 shows that in the 1970s, the maturation process was decreasing the total acidity from around 6 g/L (H_2SO_4/L) on September 1st to 4 g/L at harvest. However, today, acidity on September 1st is around 4 and 3.5 g/L at harvest. In terms of potential alcohol, four decades ago, it was around 10 %vol on September 1st, and reached approx. 12.5 %vol at harvest. Nowadays, grapes already reach 12.5 % potential alcohol at the beginning of September and are above 14 % at harvest. Lastly, even if berry weight is not a decisive factor in the harvesting of grapes, in the 1970s a significant number of days was observed between September 1st and harvest, allowing for berry growth and end of maturation, while currently there is hardly any difference between those two dates, and berries no longer grow in September.

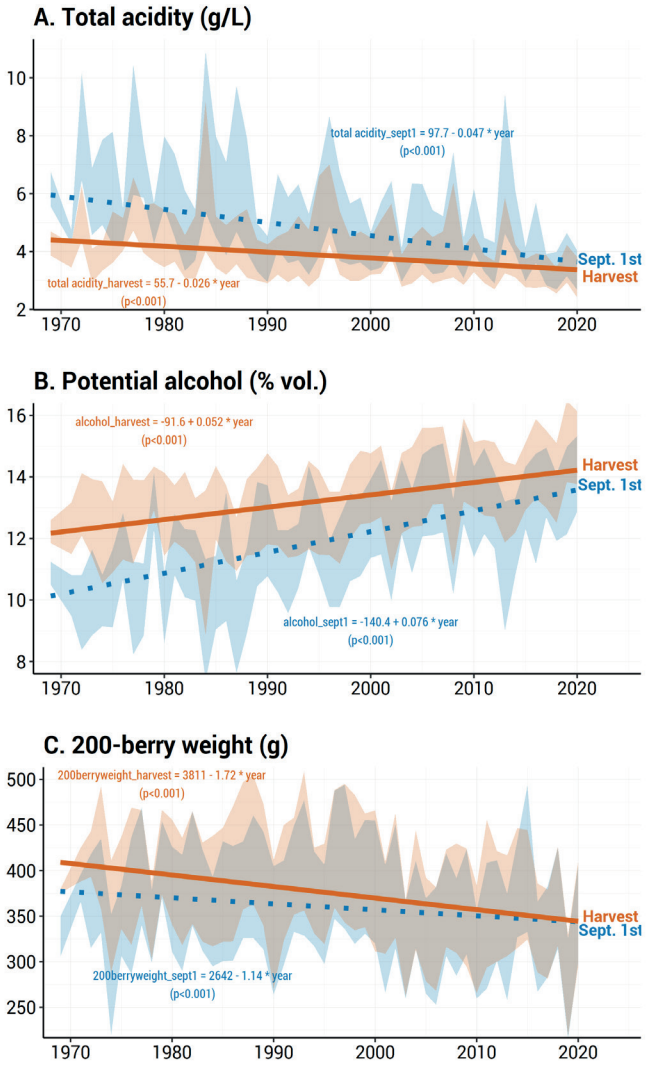


FIGURE 11. Comparison of maturity parameters on September 1st and at harvest.

A) Total acidity (g H_2SO_4/L); B) Potential alcohol (% vol.); C) Evolution of 200-berry weight (g). The orange lines represent the linear regressions of the maturity dataset at harvest. The dotted blue lines represent the linear regressions of the maturity dataset on September 1st

DISCUSSION

In this study, we explored how the changes in climatic conditions over the past 50 years have affected certain descriptors of grape maturity using what is to our knowledge the first open database of quality and yield data from a Wine Region. It was thereby not only possible to explore the characteristics of the grapes at harvest, but also to better understand the dynamics of the different variables during the period 1969–2020.

As previously mentioned, simple phenological models were also used to calculate different strategic phenological stages. These models provided important information which is needed to fill the gap in terms of the phenological observations in this area. Even if the models were not directly validated with observed local data in this study, the results obtained using regional data (see Figure 4SM) were robust enough to be used in this analysis, and they compared well with those from other models (Brin model, see García de Cortázar-Atauri *et al.,* 2009a and Morales-Castilla *et al.,* 2020) (see process-based model comparisons in Figure 3SM).

Moreover, in the present study, the ecoclimatic method for characterising specific climate impacts on the grapevine is used. This method—which is based on combining classical agroclimatic indicators calculated during specific phenological phases—was used to determine the specific effects of different climate variables on maturity traits.

1. Recent climate change has already affected the Rhône valley vineyard

The analysis of global phenology trends and different quality and quantity variables (Table 1SM) confirms results obtained in previous studies in other vineyards around the world (Jones and Davis, 2000; Ganichot, 2002; Duchêne and Schneider, 2005; Petrie and Sadras, 2008; Neethling *et al.,* 2012; Ramos *et al.,* 2015; García de Cortázar-Atauri *et al.,* 2017; Zufferey *et al.,* 2018; Koufos *et al.,* 2020). Regarding the quality and yield variables, this study goes further, as it is based on several areas in the same vineyard and a historical depth is rarely available.

As shown in other studies, all the phenological stages of grapevine now take place earlier than 50 years ago (from 10 to 20 days depending on the phenological stage), resulting in a shift of the maturation phase to the warmest periods (Figure 9SM). (García de Cortázar-Atauri, 2006; Webb *et al.,* 2007; Duchêne *et al.,* 2010; Ollat and Touzard, 2014; Marjou and García de Cortázar-Atauri, 2019).

While the analysis of correlations between maturity data and ecoclimatic indicators also confirms known relationships, such as alcohol or acidity and temperature during maturation, it also highlights less obvious relationships: 200-berry weight and the temperature and length of the fruit set to end of lag-phase.

1.1. Decrease of total acidity (and increase of pH)

We have seen that the total acidity of grapes at harvest follows a downward trend, which seems much more likely due to thermal conditions between véraison and harvest than to the other climate indicators. This is supported by the fact that high temperatures accelerate the decrease in grape acidity, mainly because of a faster degradation of malic acid (Orduña, 2010; Poni *et al.,* 2018). The acidity value measured in 2003 is another important result: despite the continuous temperature increase in recent years, 2003 remains the year with the hottest véraison to harvest period; however, the value of the observed acidity that year is not the lowest of the study period (Figure 5). This is probably because the very high temperatures were recorded just after véraison (first week of August) and that the temperatures of the following days did not accelerate the acidity decrease. The other extreme year was 1984 when both low temperature and water deficit had a direct effect on the observed total acidity values.

Another relatively important correlation appears during the Budburst-Flowering phase, with a strong early water deficit being linked to low acidity at harvest. Even if the reason for this relationship is not completely obvious, it can be hypothesised that the grapevine mineral absorption synergy between nitrogen and potassium plays a role: better nitrogen assimilation (depending on soil water availability during the spring) leads to better canopy growth and in turn to better potassium assimilation and redistribution within the canopy. Spring nitrogen and potassium absorption are key factors for acidity levels in must and wine quality (Dubernet *et al.,* 2015).

Lastly, even though a specific example of the relationship between the trends of pH and some climatic indicators is not given in the study, we highlight the fact that their significant correlations were practically the same as those of total acidity, but with an opposite tendency.

1.2. Increase in sugar and therefore potential alcohol

Nowadays, Grenache grapes are harvested at a potential alcohol level which is 2.5 % vol. higher than 50 years ago, and in terms of grape maturity on the same date (like 1 September), potential alcohol has increased by 4 % vol. The data obtained in the present study indicates that the Véraison-Harvest phase has a dominant effect on potential alcohol at harvest. Moreover, during this phase, the highest correlations indices were obtained for high solar radiation, low wet days frequency and high temperatures. It is well-known that high solar radiation and high temperatures accelerate sugar accumulation and therefore cause faster ripening (Coombe, 1987; Bergqvist *et al.,* 2001; Martínez-Lüscher *et al.,* 2015). These relationships are confirmed by the results of this study, which show a high correlation between solar radiation (during the Véraison-Harvest phase) and potential alcohol. The aforementioned phenological results (see Figure 9SM) show the effect of shifting this phase to summer periods that have more daily solar radiation and less rainfall (Figure 10SM).

Moreover, high temperatures (> 30 °C) may also contribute to higher potential alcohol due to concentration by evaporative loss (Keller, 2010). In this context, our results also show a high negative correlation between wet days frequency and potential alcohol: when the weather is wet, there is less berry drying, thus restricting potential alcohol increase by concentration. Even though this type of trend has already been observed—in particular for Syrah in Australia (Coombe and McCarthy, 2000; Rogiers *et al.,* 2004)—further studies and observations on Grenache are needed to confirm this interesting relationship.

1.3. Decrease in berry weight

The database used in the study made it possible to analyse a long series of yield-related data (here 200-berry weight). To our knowledge, few studies have evaluated this information in other vineyards for such a long period of time (Jones and Davis, 2000). One of the most important observations was the severe drop in berry weight after the 1990s. This change in trend during this period (1990s) confirm other observed trends for other crops in France (Brisson *et al.,* 2010) and in Europe (Moore and Lobell, 2015), with climate and agronomical practices having been identified as potential factors which play a role in such changes. In the present study, berry weight at harvest was found to be less correlated with ecoclimatic indicators than were acidity and sugar. However, an important impact of various climate variables (temperature, rain frequency, water deficit and humidity) on berry weight at harvest was observed during the period from fruit set to lag-phase end. This can be explained by the fact that berry weight is mainly driven by thermal conditions on phases I & II of the berry growth curve, with negative correlations between temperatures and 200-berry weight. This was also one of the hypotheses of the model developed by García de Cortázar-Atauri *et al.* (2009b), who showed that for Grenache and Syrah, the final berry weight was predetermined during this period. Moreover, it is worth noting that the lower the water deficit during this period (calculated using rainfall and evapotranspiration), the bigger the berries will be. All these results are consistent with studies that show that temperature (Hale and Buttrose, 1974; Kliewer, 1977) and water deficit negatively affect berry weight, especially between fruit set and véraison (Coombe and McCarthy, 2000; Ollat *et al.,* 2002; Ojeda *et al.,* 2001; Ojeda *et al.,* 2002; Scholasch and Rienth, 2019; Zhu *et al.,* 2020). Another interesting result is that phase length (temperature-dependent) is also a contributing factor: the longer the I & II growing phase (set-lag), the heavier the berries. It can be assumed that an acceleration in berry developmental rate has a negative effect on final berry weight, as has been observed in the grain of other species (Asseng *et al.,* 2011). Cell division in grape berries occurs during the beginning of phase I of herbaceous growth. An accelerated phase I and II (or *fruit set* to *lag phase*) will give less time for cells to divide within the berries; and thus potentially less cells will be filled up during phase III of berry growth (Coombe and Iland, 2004, Ojeda *et al.,* 1999, Ollat *et al.,* 2002). This is useful for winegrowers because it shows that a yield component is partly defined by an early stage and can explain—and allow one to anticipate—vintages such as 2019, a year when the wine region yield loss was significant and mostly due to very small berries. Lastly, humidity throughout the berry-growing period, and specifically during Véraison-Harvest, seems to be important for maintaining high berry weight, thereby preventing dehydration at the end of the maturation process. The impact of rainfall on berry weight during the lag to harvest phases is, however, much less than that of humidity. The year 2019 always showed extreme values for both indicators (even more than in 2003), which directly affected final berry weight; this was therefore the year with the lowest measured yield in the last 50 years.

2. Collecting maturity data for modelling grape profile and characterising vintage typology

The maturity network and the database used in this study have shown many potential uses. By using the database to carry out data-driven and spatialised analyses grapevine maturity change has been characterised in detail in the Côtes du Rhône appellation area in the last 50 years. Moreover, beyond such analyses, the database can be used to better characterise future vintages. An example of the management and modelling use of the network is the forecast of a grape maturity profile by:

- ➔ placing the current year (in comparison to homologous vintages during the past 50 years) as a function of climate indicators calculated during key-phenological stages. This makes it possible to anticipate the vintage type and its viticultural and oenological implications.
- ➔ collecting data on extreme climate events and their impacts on grape profile. An unusual climatic pattern during the wine-growing season may cause unknown consequences. Recording and analysing data in retrospect can lead to new agronomical and climate-change-related questions and hypotheses. Well-documented events help to improve process-based grape models.

Nevertheless, developing and maintaining this kind of network can be expensive, and it would be wise to optimise it to maintain its significance and robustness. Spatial significance can be enforced by following reference plots, from which relationships with other plots of the network are characterised.

3. Climate change and the future of grape growing in the Rhône Valley

The results given in this study highlight the significant impact of climate change in the Rhône valley. However, other human and agronomical factors which can affect the grape profile must not be neglected. Viticultural science has led to improved knowledge of vine physiology and better management of the ripening process. Innovation and major new technologies, such as mechanical harvesting, help improve reactivity and accuracy when scheduling harvest work. Today plots are harvested at optimal maturity, while in the 1970s the first harvested plots were often under-ripe because of the time needed to hand-pick a whole wine estate.

Nevertheless, the recent changes in climate conditions and expected future trends will define new challenges to be met by winegrowers in the years to come. As previously explained, the ideal conditions for grape ripening and making wine will be challenged by a temperature rise and an earlier ripening period: if the ripening period takes place in August rather than in September, when temperatures are warmer, it will lead to a faster ripening that is more difficult to control, because the concentration of sugars can increase substantially within a few days (Duchêne, 2015; van Leeuwen and Destrac-Irvine, 2017; Morales-Castilla *et al.,* 2020).

When dealing with climate change, winegrowers will need to achieve a balance between two extremes: ***enduring*** and harvesting earlier and earlier to keep a constant maturity, and ***adapting*** their system by delaying the ripening period for as long as possible to avoid very warm periods. In this sense, the analysis on the conditions on September 1st allows to take into account winegrowers' point of view and proposes another perspective to analyse the results. For the time being, winegrowers from the Rhône valley vineyard consider it difficult to harvest in August. Nevertheless, grapes ripen closer and closer to this date, affecting the organisation of work in the vineyard and requiring winemakers to adapt to the new climatic conditions. Until now, the impacts of these changes have been limited to the Rhône valley, as progress in oenology over the last few decades—especially in terms of high alcohol content—allows grapes with extreme maturity profiles to be vinified. Furthermore, a September harvest is still often a precondition in a winegrower's mind. This shows that, facing climate change, flexibility is getting lower and lower.

Viticulture in our Mediterranean context will have to adapt to overcome these challenges and stay efficient. The diversity of its grape varieties is a major strength in mitigating the effects of climate change (Morales-Castilla *et al.,* 2020). Nearly 30 grape varieties are grown in the Rhône Valley region, and some new varieties are currently being bred. These new varieties have been selected for their ability to endure climate change effects, such as tolerance to drought and heat and their later ripening cycles.

However, it is not enough to have a grape diversity strategy; it is necessary to take other factors into account:

- agronomy: grape growing techniques, agroforestry, vine management and irrigation;
- geography: better knowledge of the terroir and cooler areas to plan for a relocating of the vineyard to the most favourable production areas;
- oenology: processes aiming to manage high degrees of alcohol and low acidity;
- grape production rules: these must be adapted to the grape growing reality of the 21st century;

These strategies would need to be considered simultaneously to manage short term, medium and long-term adaptations.

CONCLUSION

This study presents the first characterisation of climate change effects on grapevine maturity and identifies the most significant climate indicators for assessing changes to Grenache grapevine maturity in the Rhône valley. Using a long-term standardised open maturity database and the SAFRAN high-resolution climate database, Grenache ripening was shown to have evolved significantly over the last 50 years with generally smaller berries, lower acidity and higher potential alcohol. These major trends were correlated with changes in phenological dates and specific ecoclimatic indicators. This study confirms various known relationships, but in a different scope and on a different scale. Moreover, it shows the importance of better observing and characterising the intermediate phenological stages that play an essential role in determining potential berry weight (end of the lag-phase). Some of the results may be used to characterise and manage future vintages.

Finally, this study shows the scientific and patrimonial value of network data which has been collected over long time periods as a tool for understanding and anticipating the changes to come. The release of the dataset under an open licence is expected to allow further analyses and comparisons to be carried out on other grape varieties or vineyards around the world, thus providing valuable indicators on the impacts of climate change on viticulture and maturity. Specific data used for this study are available at this URL: https://data.inrae.fr/dataset.xhtml?persistentId=doi:10.15454/QQDALG

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