OENO One vine & wine

DOI: https://doi.org/10.20870/oeno-one.2024.58.3.8083

OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Four decades in the vineyard: the impact of climate change on grapevine phenology and wine quality in northern Italy

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Associate editor:
Daniel Molitor

Received:
11 April 2024

Accepted:
6 August 2024

Published:
16 September 2024

ABSTRACT

The wine sector, among the most profitable agricultural segments, has been markedly affected by the ongoing climate change impacts, such as warmer climate conditions with higher frequency of extreme temperatures and a trend of decreasing precipitation. All this results in higher evaporative demand and therefore higher occurrence of water stress events leading to advancement of temperature-sensitive phenological stages (e.g., budburst and ripening). Such negative effects eventually affect berry development and quality, especially in historically valuable viticultural areas, forcing winegrowers to work within a compressed harvest period to maintain wine typicity. In this work we examined the relationship between environmental variables (air and soil temperature, relative humidity, precipitation, and solar radiation), phenology, berry, and wine quality for the two varieties (Chardonnay and Teroldego) in Trentino Alto-Adige/South Tyrol (Italy) over 36 years. Huglin Index (a bioclimatic heat index), growing degree days (measure of heat accumulation), and overall mean temperature showed linear increase ($p < 0.001$) in the last years, while no variations were recorded for precipitations. Despite no major effects being observed for phenological interval lengths, the onset of most of the phenological stages for both varieties had significantly ($p < 0.001$) advanced. However, i) early budburst pushed the budburst-flowering interphase by -1.2 days every two years toward putative colder periods with increased late frost probability and potential slower phenological progression towards flowering, and ii) early veraison shifted the veraison-ripening interphase by 0.25 day per year into warmer periods that oppositely impose faster phenological advancement. Hence, a substantial equilibrium in the seasonal growing length over years was maintained. Potential carry-over effects from the previous season were observed, particularly associated with heat requirements to unlock early phenological events, raising additional concerns on the additive effects of climate change to viticulture. Generally, white wine quality increased ($p < 0.05$) over the years, while red and sparkling wines remained unaffected. This was putatively related to accurate harvest date decision-making dictated by berry quality parameters: sugar-to-acidity ratio for Chardonnay and bunch sanitary status for Teroldego. Overall, this work provides evidence of the dynamics involved in climate change, and, to our knowledge, its overlooked effects on viticulture, thus providing new insights that can contribute to further developing adaptive strategies.

KEYWORDS: Climate change, grapevine, phenology, viticulture, growing degree days, late frost, wine quality

INTRODUCTION

Historically, viticulture has thrived in agricultural contexts in which wine typicity is defined by the interplay of the cultivar with the environment, pedological features and rootstock (Reynolds, 2021; Stefanis *et al.*, 2023; van Leeuwen and Seguin, 2006). In most viticultural areas, this contact point has been the basis for the establishment of a prosperous and economically important industry (Alston and Sambucci, 2019; Meloni and Swinnen, 2018; OIV, 2022). As with any farming system, this virtuous loop has always been subjected to unpredictable meteorological dynamics (Bucur and Babes, 2016), which can diminish or increase berry quality and productivity (Baciocco *et al.*, 2014; Salinger *et al.*, 2015) via a series of erratic environmental conditions, such as low or high temperature (Buttrose, 1974; Downey *et al.*, 2006; Eltom *et al.*, 2017; Hendrickson *et al.*, 2004; Keller, 2010; Kliewer, 1977; Mori *et al.*, 2007; Petrie and Clingeleffer, 2005; Sweetman *et al.*, 2014), hailstorm (Fernández-Mena *et al.*, 2023; Petoumenou *et al.*, 2019; Rana *et al.*, 2022), and low or high rainfall (Gambetta *et al.*, 2020; Grimes and Williams, 1990; Keller *et al.*, 2008; Keller *et al.*, 2016; Mirás-Avalos and Intrigliolo, 2017; Williams *et al.*, 2010). All these can act either directly (e.g., bunch and/or canopy damages) (Gambetta *et al.*, 2021; Petoumenou *et al.*, 2019) or indirectly (e.g., higher incidence of pathogens infection) (Bois *et al.*, 2017; Reineke and Thiéry, 2016; Seem *et al.*, 2000) on the vineyard, making their prediction complex and sometimes spurious (Beauchet *et al.*, 2020; Fraga *et al.*, 2016; González-Fernández *et al.*, 2020; Molitor *et al.*, 2020). In recent years, specific and long-term environmental trends have been observed in many viticultural areas, with a general increase in thermal accumulation (Droulia and Charalampopoulos, 2022; Duchêne and Schneider, 2005; IPCC, 2022; Schultze *et al.*, 2016b; Venios *et al.*, 2020), evaporative demand (Duchêne and Schneider, 2005; van Leeuwen *et al.*, 2019) and phenological advancement (Alikadic *et al.*, 2019; Bock *et al.*, 2011; Cameron *et al.*, 2021, 2022; De Cortázar-Atauri *et al.*, 2017; Dinu *et al.*, 2021; Tomasi *et al.*, 2011; Xyrafis *et al.*, 2022), potentially enhancing the risk of water limitation (Santos *et al.*, 2020; van Leeuwen *et al.*, 2019) multifactorial stress occurrence (Santos *et al.*, 2020; van Leeuwen *et al.*, 2019) and a general advancement in berry ripening that occurs over periods during which higher temperatures and lower precipitation are expected (Cameron *et al.*, 2020; De Cortázar-Atauri *et al.*, 2017; Kurtural and Gambetta, 2021).

Phenological onset in grapevine fixes the occurrence of certain physiological processes associated with productivity and quality. Advancing or delaying any phenological onset pushes the subsequent phenological stage towards periods with a higher probability of warm and cold conditions respectively, thus imposing possible additive effects (Cameron *et al.*, 2022; Keller, 2023; Lorenz *et al.*, 1995; Mosedale *et al.*, 2016). This trend has been shown to be curvilinear when large thermal variation is included, suggesting that the rate of decrease in specific interval length will slow until a plateau is reached, potentially due to trade-offs with temperature conditions (Cameron *et al.*, 2022). However, to date, a large amount of information corroborates a linear progression in grapevine phenological onset, and hence harvest date, in a series of viticultural areas in several countries (e.g., Australia, California, Greece, France, Luxembourg, and Italy), indicating that generally changing climate still has a direct effect on phenological dynamics (Cameron *et al.*, 2020, 2021; Cuccia *et al.*, 2014; De Cortázar-Atauri *et al.*, 2017; Jarvis *et al.*, 2019; Koufos *et al.*, 2018; Koufos *et al.*, 2020; Koufos *et al.*, 2022; Molitor *et al.*, 2020;Molitor and Junk, 2019; Morales-Castilla *et al.*, 2020; Tomasi *et al.*, 2011; Xyrafis *et al.*, 2022).

It is known that wine grape varieties display a plethora of optimum temperature ranges within which they can produce high-quality wines, hence implying the possibility of using different varieties for future climatic contexts (Duchêne *et al.*, 2012; Fortes and Gallusci, 2017; Keller, 2023; van Leeuwen *et al.*, 2019). However, switching variety is often complex for the wine industry because of the losses in varietal connotation, wine typicity, and oenological knowledge associated with such a choice. Therefore alternative paths are adopted by viticulturists to avoid the abovementioned negative effects of global warming, such as elevational shifts of new vineyards and/or expensive agronomic practices with the aim of synchronise ripening dynamics and/or protecting bunches from excessive radiation and temperature (Alikadic *et al.*, 2019; Arias *et al.*, 2022; Bertamini and Faralli, 2023; Faralli *et al.*, 2022; Centinari *et al.*, 2018; Gambetta *et al.*, 2021; Poni *et al.*, 2022).

Most studies published to date agree on the major role of temperature in vine physiology and phenology (Cameron *et al.*, 2021; Parker *et al.*, 2020; Schultze *et al.*, 2016a; Venios *et al.*, 2020), focusing mainly on the timing of different phenological stages and on the direct effect of temperature on single variables. However, there is a lack of area-specific studies which enable detailed analysis of the mutual relationships among a wide range of environmental and phenological data.

This work aims at unravelling the effects of climate change on the grapevine growth cycle and wine quality by analysing the time series of environmental and phenological data collected in the period 1986-2022 in two vineyards located in northern Italy (Trentino Alto-Adige). Indeed, understanding the historical trend in terms of functional processes (i.e., phenology and ripening) alongside specific meteorological events may be a milestone in further defining novel adaptation strategies via genetic improvement or vineyard management.

MATERIALS AND METHODS

1. Study sites and vineyards

This study is based on a multi-decennial data collection (from 1986 to 2022) from two vineyards located in Piana Rotaliana in the Autonomous Province of Trento, Trentino Alto-Adige/South Tyrol region, Italy (see Figure 1).

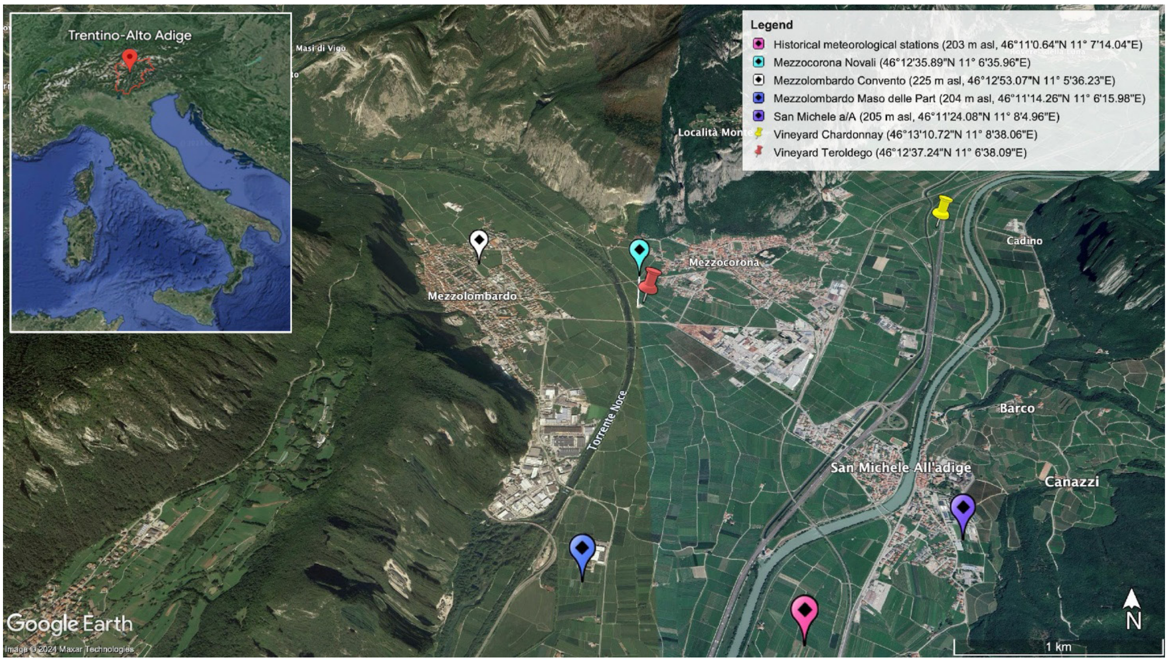

FIGURE 1. Insert: the location of the study area in the Trentino-Alto Adige/South Tyrol region in Italy. Main image: Map of the Piana Rotaliana winegrowing area (Val d'Adige). Pushpins indicate the locations of Chardonnay and Teroldego vineyards, paddles indicate the locations of the weather stations. Names, coordinates and altitudes of the locations are reported in the legend.

The two vineyards were planted with Chardonnay (SMA130 clone) and Teroldego (SMA138 clone) grape varieties in 1980. The Chardonnay vineyard was located in Carost (or Chiarost), between Mezzocorona and Roverè della Luna. Scions were grafted onto SO4 rootstock and trained as *"pergola doppia"* with a plant density of 5.5 x 0.625 m. The Teroldego vineyard was located in Novai, between Mezzocorona and Mezzolombardo. Scions were grafted onto 101/14 rootstock and trained as *"pergola doppia"* with a plant density of 6 x 0.5 m. Both vineyards have recently been replanted (Chardonnay in 2015 and Teroldego in 2018) and the monitoring site has been consequently replaced respecting the same area, training system and pedoclimatic conditions (i.e., the adjacent vineyards from 2016 in Chardonnay and 2018 in Teroldego).

2. Meteorological data and viticultural agroclimatic indices

The available dataset consists of a long time-series, from 1986 to 2022, of meteorological and phenological data, collected in the two vineyards described above. The environmental historical series, recorded by meteorological stations located one kilometre from the vineyards (Figure 1) and available on a daily and/or hourly scale, includes: daily mean, maximum and minimum air temperature (°C); mean soil temperature (°C); mean relative humidity (%); precipitation (mm); solar radiation (MJ/m^2); and reference evapotranspiration (ET$_0$). The meteorological data were validated after a comparison with those recorded by three nearby public meteorological stations (Figure 1): namely Mezzolombardo Convento recording from 1921 to 2006; Mezzolombardo Maso delle Part recording from 2012; and San Michele all'Adige recording from 1926 to 2005. This same check was also carried out with the data recorded by the Mezzocorona Novali meteorological station active since mid-1999 and much closer to the survey site (Figure 1). The comparison showed a strong similarity in the overlapping periods, and therefore the Mezzocorona Novali data were used to fill small gaps in the original series, allowing long time series of continuous and homogeneous data to be obtained. Gap filling was not performed by interpolations to avoid introducing inhomogeneities and errors in the historical series.

3. Calculation of agroclimatic indices

Growing degree days (GDD) were calculated annually (between 1 January and 31 December of each given year) using a base temperature (*Tbase*) of 10 °C, 7.2 °C and 6 °C, as follows:

$$GDD_{Tbase} = \frac{Tmax + Tmin}{2} - Tbase$$

where *Tmax* is the daily maximum temperature and *Tmin* is the daily minimum temperature (Jones *et al.*, 2010; McMaster and Wilhelm, 1997). For all the base temperatures, we assigned a daily value of 0 when the mean temperature was below *Tbase*. GDD are extremely helpful for predicting phenological onsets (Camargo-Alvarez *et al.*, 2020; Piña-rey *et al.*, 2021; Zapata *et al.*, 2015) and they offer a hint of the potential ripening of varieties and of the wine styles that can be produced when classified according to the Winkler region (Anderson *et al.*, 2012; Charalampopoulos *et al.*, 2024).

However, different *Tbase* were needed to better evaluate the potential effect of *Tbase* on estimating BBCH07 (green tip), especially due to cultivar-specificity of this parameter (de Cortázar-Atauri *et al.*, 2009; Laurent *et al.*, 2020, Faralli *et al.*, 2024).

The De Martonne index (DM), an aridity parameter used worldwide to identify dry/humid climate conditions (García-Martín *et al.*, 2022; Szűgyi-Reiczigel *et al.*, 2022), is calculated as follow:

$$DM = \frac{P_{annualmean}}{T_{annualmean} + 10}$$

where DM varies with values less than 10 for arid conditions to values above 55 for extremely wet conditions.

The Huglin Heliothermic Index (HI) [°C], a bioclimatic heat index calculated as the temperature sum over a temperature threshold of 10 °C, summed for all days from beginning of April to end of September, is calculated as follows:

$$HI = \sum_{1stApril}^{30thSeptember} \left[\frac{(Tmean - 10) + (Tmax - 10)}{2} * k\right]$$

where *Tmean* is daily mean temperature, *Tmax* is daily maximum temperature, and k (the daylength coefficient) is equal to 1.05 according to the latitude of the vineyards (Jones *et al.*, 2010). A daily value of 0 was assigned when the temperatures (*Tmean* and/or *Tmax*) were below 10 °C.

In addition, the number of days exceeding the temperature thresholds of 30 °C and 35 °C were calculated for each year, while seasonal and annual variables were assessed by aggregating the original variables by means (e.g., for temperature and humidity) or by sums (e.g., for precipitation, solar radiation, evapotranspiration, GDD and HI). In the years with data gaps temporal aggregations were avoided. For the scope of this work, seasons were conventionally divided as follows: winter from January to March, spring from April to June, summer from July to September, and autumn from October to December. Temporal aggregations were also carried out for the period 1 April to 30 September, considered representative of the grapevine developmental cycle, and for the period 15 May to 15 June, critical for the productivity of the vineyard in the following year due to bud differentiation (Petrie and Clingeleffer, 2005).

4. Phenological data, berry quality and wine rating

Phenological data comprise a historical series of day of the year (DOY) corresponding to the onset of key phenological phases in Chardonnay and Teroldego (e.g., BBCH07 "Beginning of bud burst: green shoot tips just visible"; BBCH15 "Five leaves unfolded"; BBCH18 "Eight leaves unfolded"; BBCH61 "Beginning of flowering: 10 % of flower- hoods fallen"; BBCH65 "Full flowering: 50 % of flowerhoods fallen"; BBCH75 "Berries pea-sized, bunches hang"; BBCH81 "Beginning of ripening: berries begin to brighten in colour"; BBCH85 "Softening of berries"), which were assessed by the same operator via visual observation of both vineyards over the 1986-2022 period and following the Lorenz *et al.*, (1994) scale. Harvest date, a technical parameter depending on the oenological aim rather than a proper phenological phase, was included. Wine quality data were available as well, covering white and sparkling wine quality for Chardonnay and red wine quality for Teroldego. The evaluation was carried out by the wine producer, Mezzacorona Sca, with an index ranging from 1 to 5 for increasing quality, as a routine practice. Other evaluations were not available. Sugar concentration measurements of Babo grade (°Ba) and total acidity (g/L) of Chardonnay and Teroldego berries were recorded. Sampling took place on different dates each year, in the weeks preceding harvest.

5. Data analysis

The analyses were performed using the software Excel (Microsoft 2022) and R (R Core Team 2022). Correlation analysis (Pearson correlation) was performed to assess the relationships between changes in phenological variables and possible concurrent drivers. Additionally, trend analysis was applied to the couples of variables that showed the strongest statistically significant ($p < 0.05$) relationships. The data set was first displayed graphically (i.e., via scatterplots and boxplots), and the main statistics of all the available variables (i.e., averages, maximums, minimums and quantiles) were calculated to unravel the potential presence of outliers and to check data quality. Hence, the data were validated after the removal of outliers verified on a case-by-case basis (in total, three outliers were detected overall on environmental data). Trends were then calculated by applying the Mann-Kendall test with a significance level of alpha = 0.05 (Supplementary Table 2), and linear models were fitted by least-squares through R statistical software package "*stats*" and the function "*lm*" for fitting linear models and computing the p-value. Only statistically significant trends are reported in the results of this study (see figures). Pearson's correlation was calculated to estimate the level of correlation between all the couples of variables. The statistical significance of the correlations was evaluated with a significance level of alpha = 0.05. In addition, the available data included several measurements of berry quality parameters sampled on different days during the ripening period (every year since 1986 to 2022). With the aim of investigating the effect of climate change on harvest decision, the DOY of the measures was transformed into days to harvest (see the abscissa of Figure 11F, given the days of harvest of Chardonnay and Teroldego for each year). In addition, we linearly interpolated the intra-annual measures when the time elapsed between two consecutive samples was less than two weeks, assuming the error made with this approximation could be neglected compared to the uncertainty of sampling. Such an approach allowed us to have continuous Babo grade and acidity data every year, from the first sampling day (i.e., about 40 days before harvest) to the day of harvest itself every year. Finally, fixing the day to harvest for each year, we calculated the annual trends of Babo grade and acidity (with significance level alpha = 0.05). The correlation analysis (Pearson) was performed by means of the R statistical software package "*stats*". The correlations between all the couples of variables were illustrated by means of a correlation matrix, in which the colour of each cell of the matrix represents the value of the correlation coefficient between the variables of the corresponding row and column. The R package used for this plotting method is "*corrplot*", which also allowed the non-significant correlations to be hidden.

RESULTS

1. Environmental and agroclimatic indices trends over years

From 1986 to 2022 and for the area considered (i.e., Piana Rotaliana in Trentino-Alto Adige/South Tyrol), a significant ($p < 0.001$, $R^2 = 0.43$) increase in annual mean temperature was

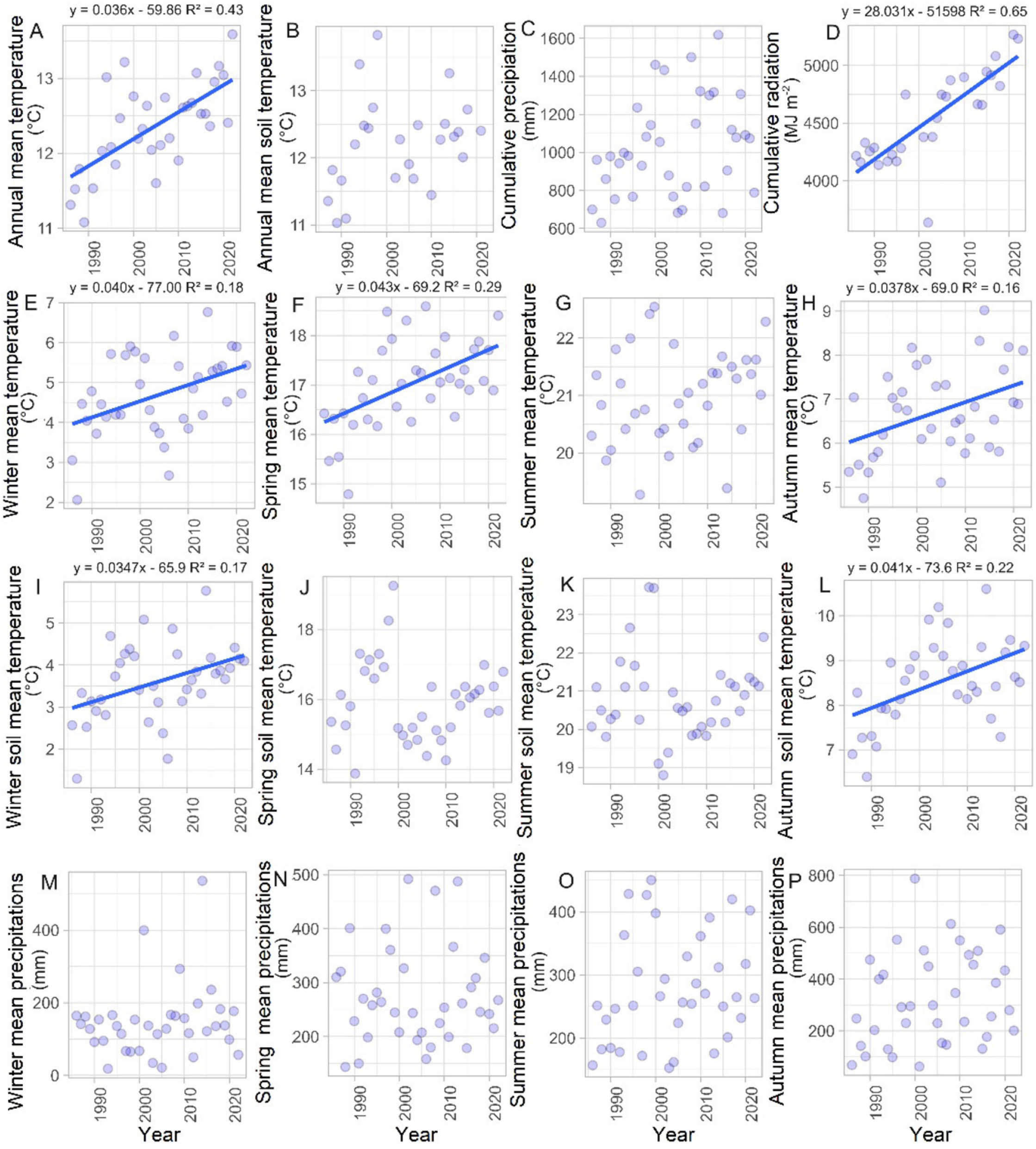

FIGURE 2. Trends between 1986 and 2022. A) Annual mean air temperature; B) annual mean soil temperature; C) cumulative annual precipitations; D) cumulative annual radiation; E), F), G) and H) average winter, spring, summer, and autumn air temperature respectively; I), J), K) and L) average winter, spring, summer, and autumn soil temperature respectively; M), N), O) and P) cumulative winter, spring, summer, and autumn precipitations respectively. Only significant relationships ($p < 0.05$) are shown in the graphs. Linear model equations referring to relationships between the studied parameters, along with the corresponding R^2 are shown in the graphs for significant models only.

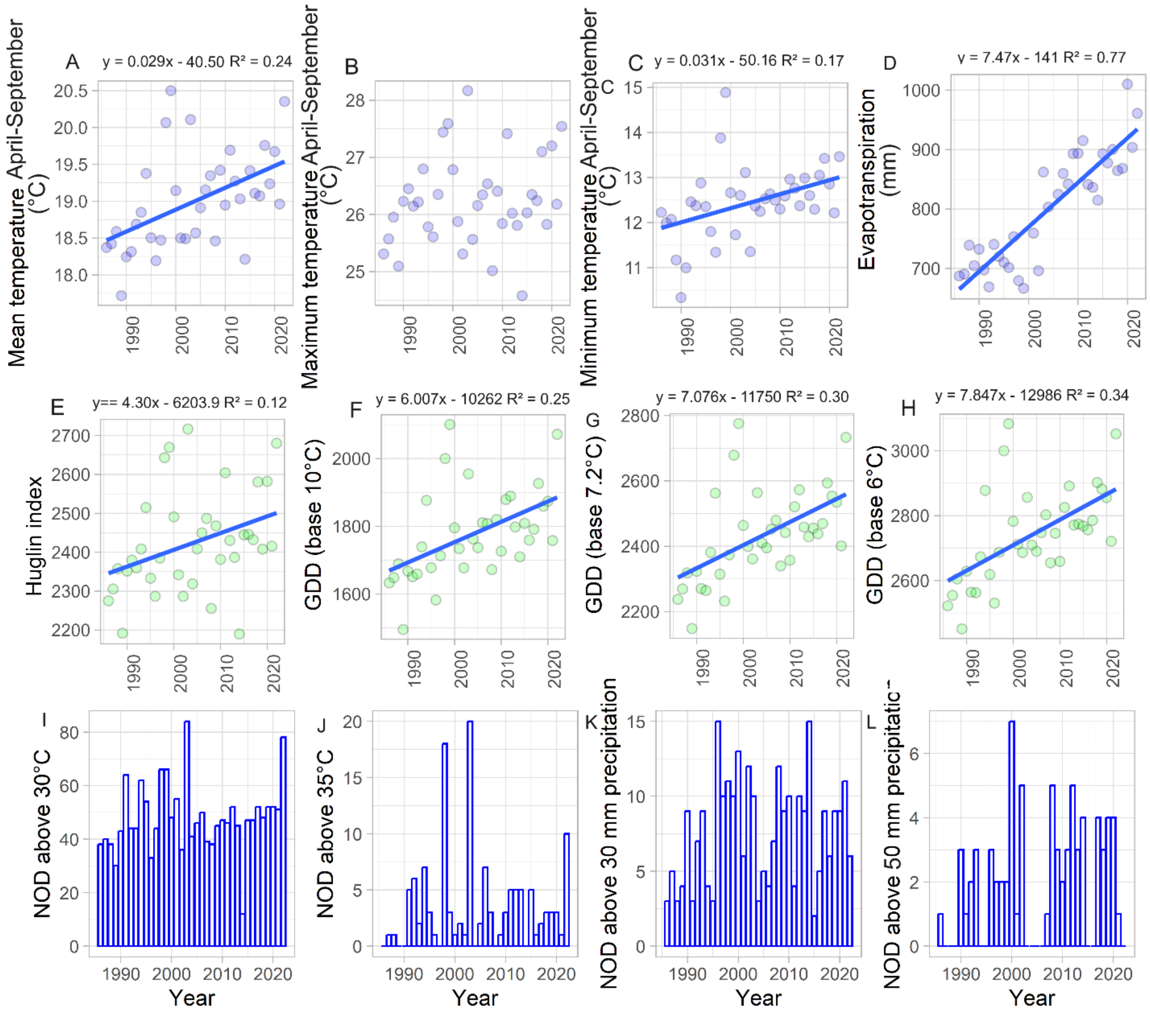

FIGURE 3. Environmental and agroclimatic indices trends between 1986 and 2022. A) Mean air temperature for the period April to September; B) maximum air temperature for the period April to September; C) minimum air temperature for the period April to September; D) evapotranspiration; E), F), G) and H) Huglin index, GDD$_{10}$, GDD$_{7.2}$, and GDD$_{6}$ respectively; I) Number of days (NOD) with temperature above 30 °C; J) Number of days (NOD) with temperature above 35 °C; K) and L) Number of days (NOD) with precipitation above 30 and 50mm respectively. Only significant relationships ($p < 0.05$) are shown in the graphs. Linear model equations referring to relationships between studied parameters, along with corresponding R² are shown in the graphs for significant models only.

observed (Figure 2A). Between the coldest year of the dataset (1989) and the hottest (2022), the mean temperature delta was 2.51 °C, with an increase of 0.108 °C every three years (i.e., 0.036 °C/year), estimated via linear regression. By contrast, there were no significant trends ($p > 0.05$) for annual mean soil temperature and cumulative precipitation (Figure 2B and C). When radiation was plotted as yearly cumulative, a significant ($p < 0.001$, $R^2 = 0.65$) and linear trend was observed, with a general increase of 28 MJ/m^2 per year and a delta of 978 MJ/m^2 between 1989 and 2022 (Figure 2D). When the annual values were divided according to seasons, significant increases in temperature values ($p < 0.001$) were only observed for spring (0.13 °C every three years), winter (0.12 °C every three years) and autumn (0.11 °C every three years) (Figure 2E-H). However, the largest differences between 1989 and 2022 were detected for autumn mean temperature, in which a differential of 3.35 °C was observed (1.39 and 2.85 °C for winter and spring respectively). Winter and autumn seasonal mean soil temperatures showed significant trends ($p < 0.001$) between years as well (Figure 2I-L). No significant differences ($p > 0.05$) were observed for seasonal dynamics of precipitations (Figure 2M-P).

The environmental data associated with the growing season (i.e., from March to August) of grapevine confirmed the annual/seasonal trends (Figure 3). Overall, a significant ($p < 0.001$) increase in average and minimum air temperature of up to 0.093 °C was observed from 1986 to 2022 every three years. Similarly, a significant ($p < 0.001$) and linear increase in reference evapotranspiration was noted, with a

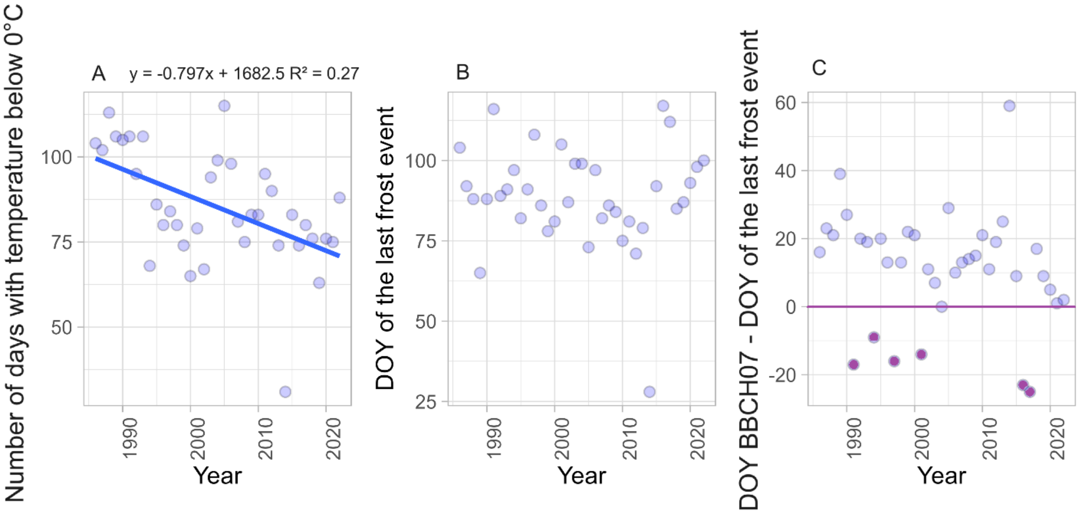

FIGURE 4. A) Number of days with temperatures below 0 °C over the years; B) day of the year in which the last frost event occurred, and C) the day of the year in which budburst occurs for Chardonnay subtracted from the day in which the last frost event occurs. In C) negative values (purple circles) represent years in which frost events occurred after budburst (i.e., BBCH07). Data were analysed via liner regression, and only significant relationships ($p < 0.05$) are shown in the graphs. The linear model equations referring to the relationships between the studied parameters, along with the corresponding R^2 are shown in the graphs and for significant models only.

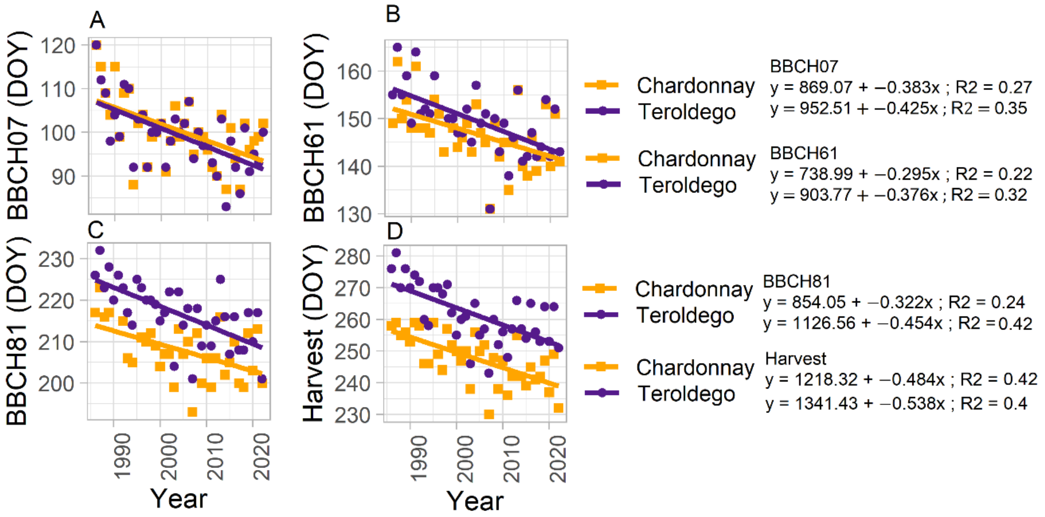

FIGURE 5. Major phenological events onset between 1986 and 2022 for Chardonnay and Teroldego as occurrence on day of the year (DOY). BBCH07 corresponds to budburst (A); BBCH61 corresponds to 10 % flowering (B); BBCH81 corresponds to 10 % veraison (C); and (D) represents harvest date. Other BBCH scale points are not pictured since priority was given to pivotal phenological stages. Yellow squares represent cv. Chardonnay while purple circles represent Teroldego. Data were collected by the same operator and on the same vineyards throughout the years. Data were analysed via linear regression and only significant relationships ($p < 0.05$) are shown in the graphs. Linear model equations referring to relationships between studied parameters, along with corresponding R^2 are shown in the graphs and for significant models only.

difference in evaporative demand of 230mm between the periods 1986-1990 and 2018-2022. No significant trend was detected for maximum air temperature. All these trends were confirmed by a series of agroclimatic indices, with a significant ($p < 0.001$) increase in Huglin Index and GDD_{10}, $GDD_{7.2}$ and GDD_{6}. Notably, GDD_{10} increased from an average of ~1600 between 1986-1990 up to ~1850 on average for 1998-2022. Temperature and rainfall anomalies were also calculated, revealing minimal and non-significant trends over the years. There was a minimal ($R^2 = 0.07$) trend for yearly number of days above 30 °C, which, however, was not significant ($p = 0.12$).

When frost events were included as days with temperatures below 0 °C, a significant and linear reduction ($p < 0.001$, $R^2 = 0.27$) was observed (0.8 day/year; Figure 4A). However, while the last frost event DOY shows significant interannual variability, it is not significant over the years (Figure 4B). When Chardonnay budburst DOY was subtracted from the last frost event DOY, no trends were observed. However, some historical late frost events were confirmed (i.e., negative values for, for example, 1997, 2016 and 2017), and a general tendency for near-zero to negative values can be observed (Figure 4C).

2. Phenological dynamics associated with climate change

Even though Chardonnay and Teroldego displayed similar budburst dates, they differed for veraison and harvest dates, with a generally earlier onset for Chardonnay (Figure 5). When the occurrence of specific phenological phases (defined as day of the year (DOY) on which they occured) are

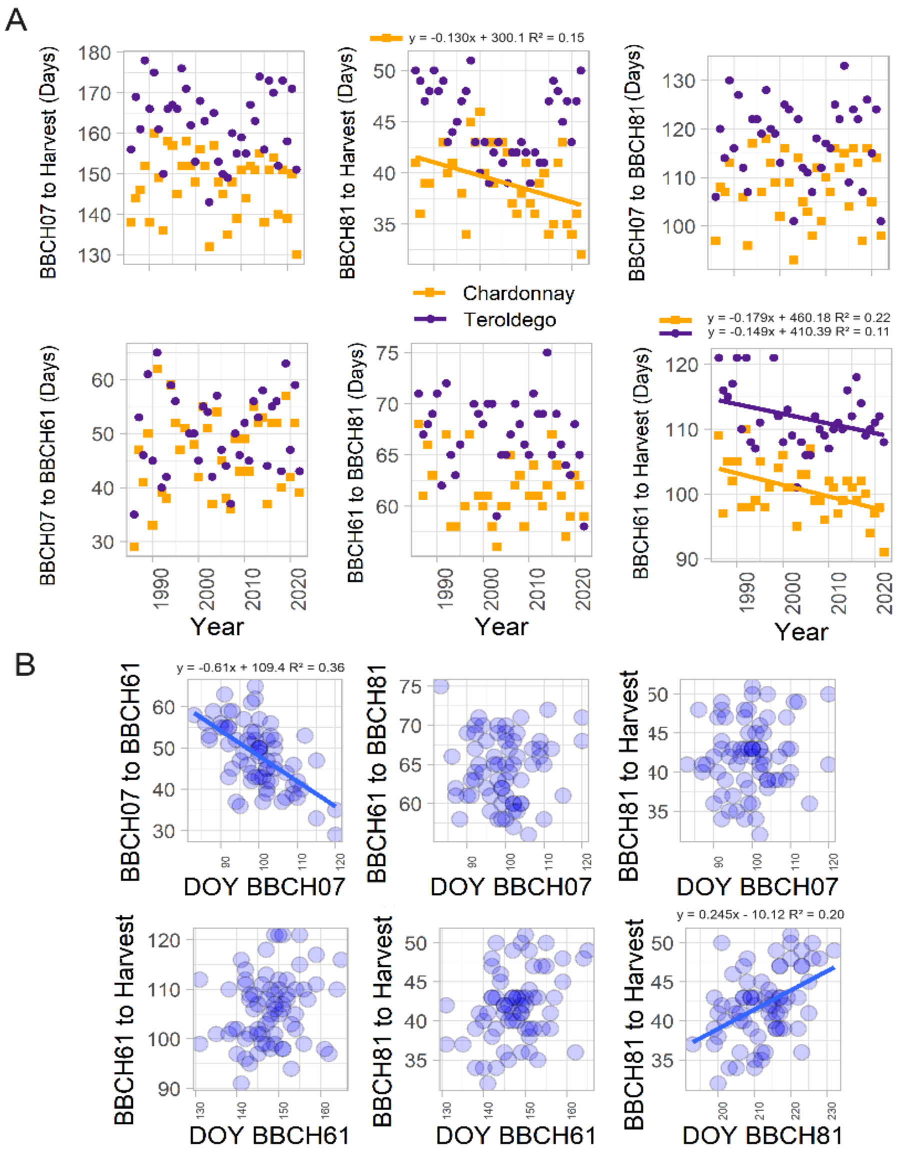

FIGURE 6. A) Length of phenological interphases (in days) calculated from phenological data and plotted against year of occurrence. BBCH07 represents budburst, BBCH 61 represents 10 % flowering, and BBCH81 represents veraison. Data were analysed via liner regression and only significant relationships ($p < 0.05$) are shown in the graphs. The linear model equations referring to the relationships between the studied parameters, along with the corresponding R^2 are shown in the graphs and for significant models only. B) Length of phenological interphases (in days) calculated from phenological data and plotted against the occurrence of specific phenological stages. Data were analysed via liner regression, and only significant relationships ($p < 0.05$) are shown in the graphs. The linear model equations referring to the relationships between the studied parameters, along with the corresponding R^2 are shown in the graphs and for significant models only.

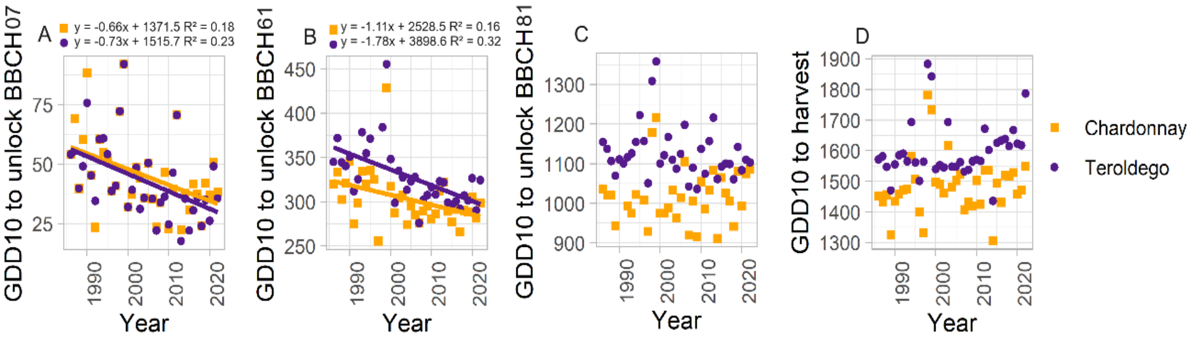

FIGURE 7. Growing degree days on base 10 °C to unlock specific phenological stages from 1986 to 2022. In A) GDD_{10} to unlock early budburst (BBCH07) in Chardonnay and Teroldego; in B) GDD_{10} to unlock early (10 %) flowering (BBCH61) in Chardonnay and Teroldego; in C) GDD_{10} to unlock early (10 %) veraison (BBCH81) in Chardonnay and Teroldego; in D) GDD_{10} to reach harvest in Chardonnay and Teroldego. Data were analysed via liner regression, and only significant relationships ($p < 0.05$) are shown in the graphs. The linear model equations referring to the relationships between the studied parameters, along with the corresponding R^2 are shown in the graphs and for significant models only.

plotted against years (see Figure 5), significant ($p < 0.001$) negative linear trends can be observed. In general, budburst occurred around mid-late April for both varieties between 1986 and 1990. However, a significant ($p < 0.001$) earlier occurrence of budburst between mid-March and early April was discernible in the most recent years of the dataset (i.e., from 2000 onwards). Similar advancements in flowering and veraison were observed with a general significant ($p < 0.001$) tendency for early phenological onset. Harvest date has also been affected over the last forty years: in the mid-1980s, Chardonnay was harvested around mid-September, while in 2022 it was harvested on 20 August. Similarly, Teroldego's harvest took place on average in early October between 1986 and 1900, while in 2022 it started on 8 September. Overall, all the phenological occurrences showed an advancement over time of between 0.3 and 0.5 day/year, resulting in an overall advancement of between 20 and 30 days from 1986 to 2022.

Phenological intervals (i.e., the number of days required to unlock a subsequent phenological event) were calculated from the initial phenological data (Figure 6A). Overall, two major interphases showed significant compression ($p < 0.001$) in the last 36 years: those of veraison to harvest date and flowering to harvest date. The interval length between veraison and harvest date showed a significant reduction for Chardonnay only ($p < 0.001$, $R^2 = 0.15$), while for Teroldego the trend was not statistically significant. Conversely, the interval length between flowering and harvest showed a significant reduction ($p < 0.001$) in number of days for both varieties, decreasing from an average duration of 115 and 105 days (Teroldego and Chardonnay respectively) in 1986-1990 to an average of 110 and 95 days (Teroldego and Chardonnay respectively) in 2018-2022. No significant reductions in length were observed for other phenological interphases. Plotting the average phenological events occurrence in DOY (Figure 6B) for the two varieties to define phenological intervals highlighted two specific trends: late budburst, generally resulting in lower and near-proportional (1.2 days every two years) budburst-to-flowering interval length ($p < 0.001$, $R^2 = 0.36$); and delayed veraison, yielding a significant increase (0.25 day/year) in the veraison-to-harvest interval length ($p < 0.001$, $R^2 = 0.20$). No significant trends were observed for the other associations (Figure 6B).

3. New insights into environment-phenology-quality interactions

Significant negative relationships were observed between the growing degree days necessary to unlock specific phenological stages and the years. A significant reduction ($p < 0.05$) in GDD_{10} was noted for reaching BBCH07 over the years (Figure 7A). Similar trends were found between Teroldego and Chardonnay, and a reduction in GDD_{10} was also found for the unlocking of flowering time ($p < 0.05$, Figure 7B). No trends were observed for heat requirements for unlocking BBCH81 and harvest (Figure 7C and D).

The correlation matrix shown in Figure 8 includes the statistically significant correlations between phenological, environmental and quality variables of the same year. The significant correlations between the onset of subsequent phenological phases and for both varieties confirmed that any delay or anticipation of a given phenological phase results in a similar behaviour of the following phenological phases. As expected, there was an inverse correlation between phenological onset DOY and the thermal accumulation variables. Regarding inter-cultivar variation, in Chardonnay, precipitation was inversely associated with the flowering-veraison interphase and annual evapotranspiration was inversely proportional to the time between veraison and harvest. Conversely, for Teroldego, precipitation was positively correlated with the length of the budburst-veraison and flowering-veraison interphases, while it was inversely proportional to the time between veraison and harvest.

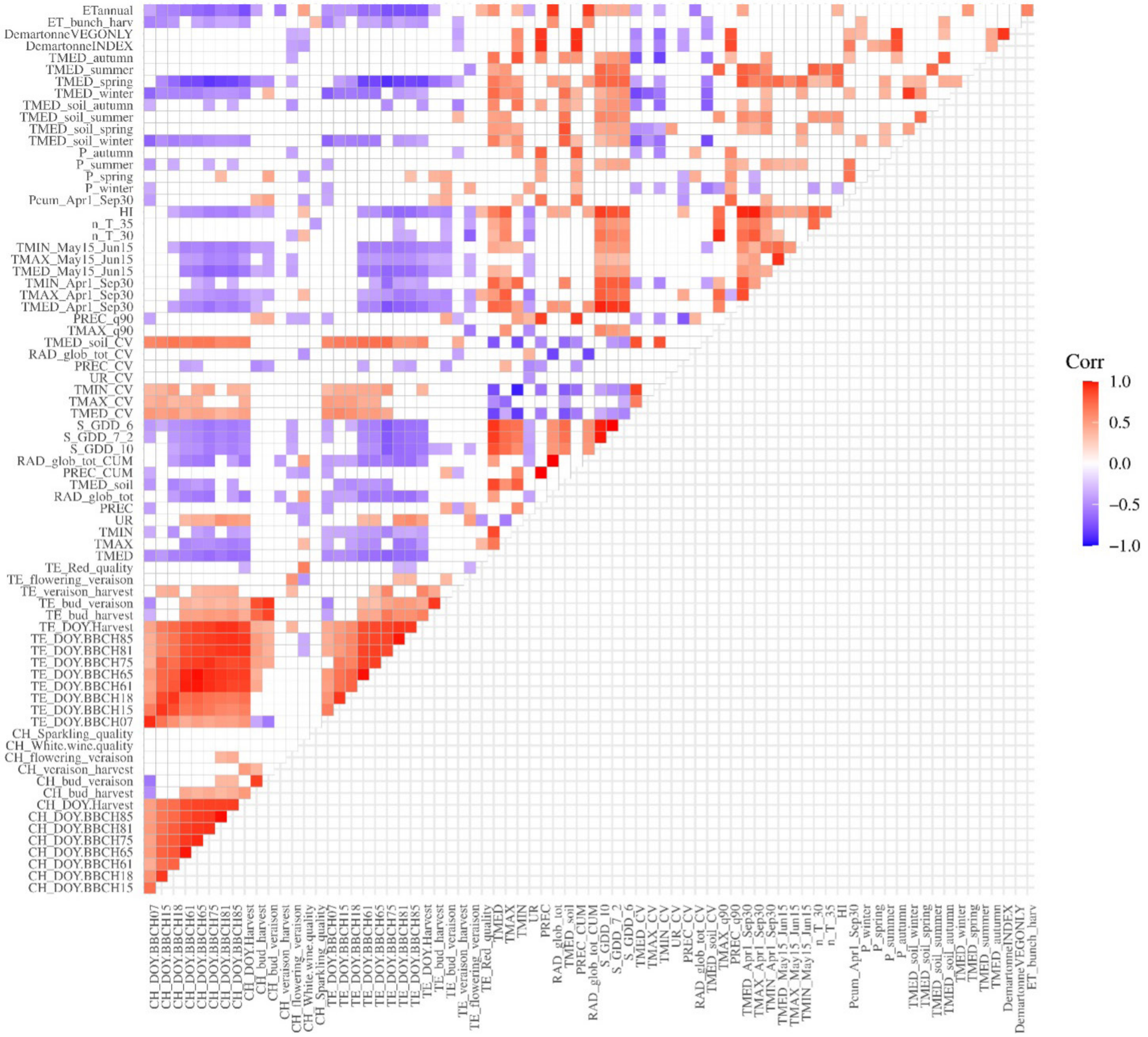

FIGURE 8. Correlation matrix showing the significance of linear correlations between phenological, environmental and quality variables of the same year. Colours are Pearson product–moment correlation coefficients and white square represent non-significant correlations. The descriptions of the acronyms are reported in Supplementary Table 1.

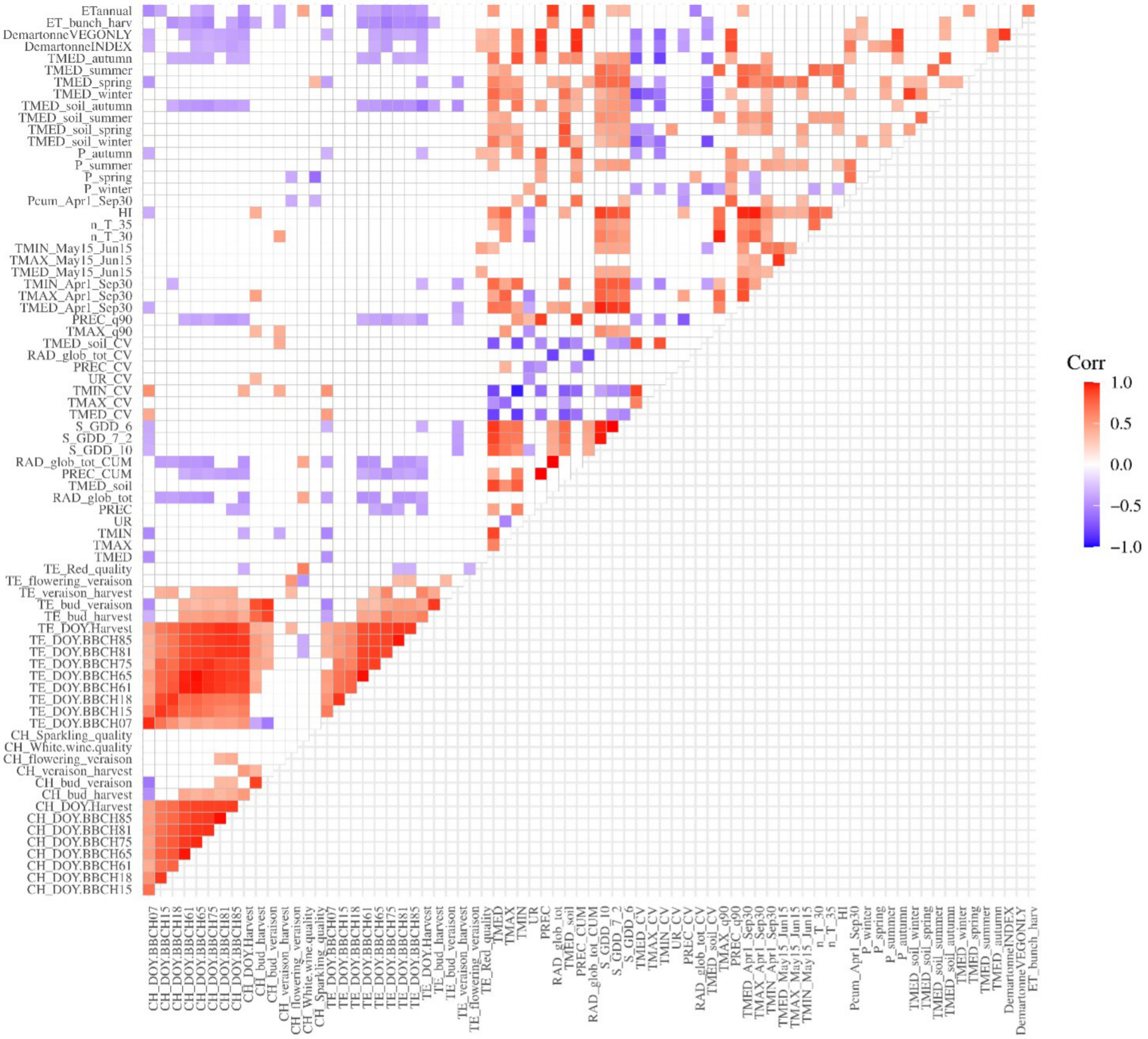

FIGURE 9. Correlation matrix showing the significance of linear correlations between phenological and quality variables with the environmental data of the previous year. Colours are Pearson product–moment correlation coefficients and white square represent non-significant correlations. The descriptions of the acronyms are reported in Supplementary Table 1.

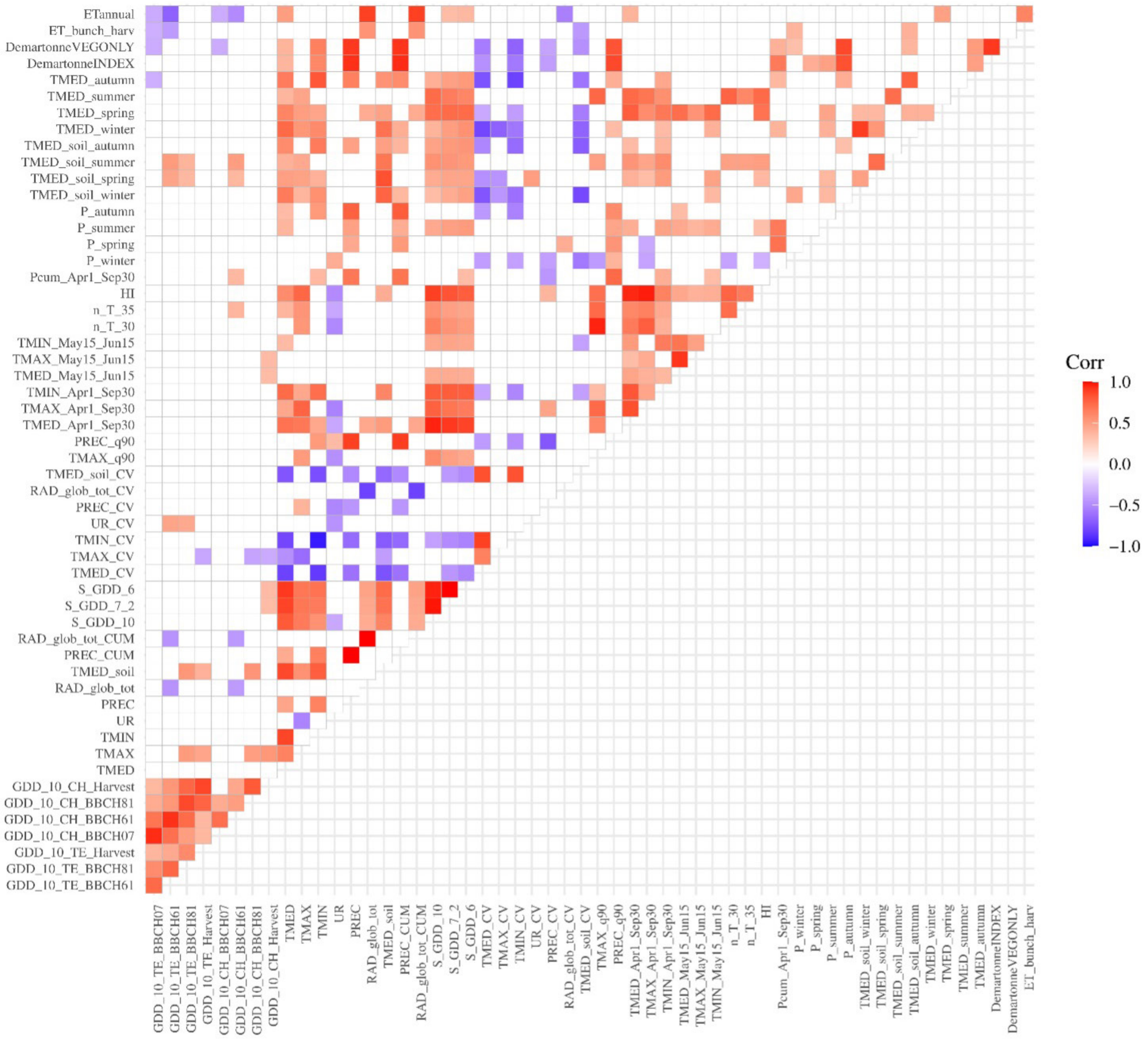

FIGURE 10. Correlation matrix showing the statistically significant correlations between heat requirements to unlock a phenological stage with the environmental data of the previous year. Colours are Pearson product–moment correlation coefficients and white square represent non-significant correlations. The descriptions of the acronyms are reported in Supplementary Table 1.

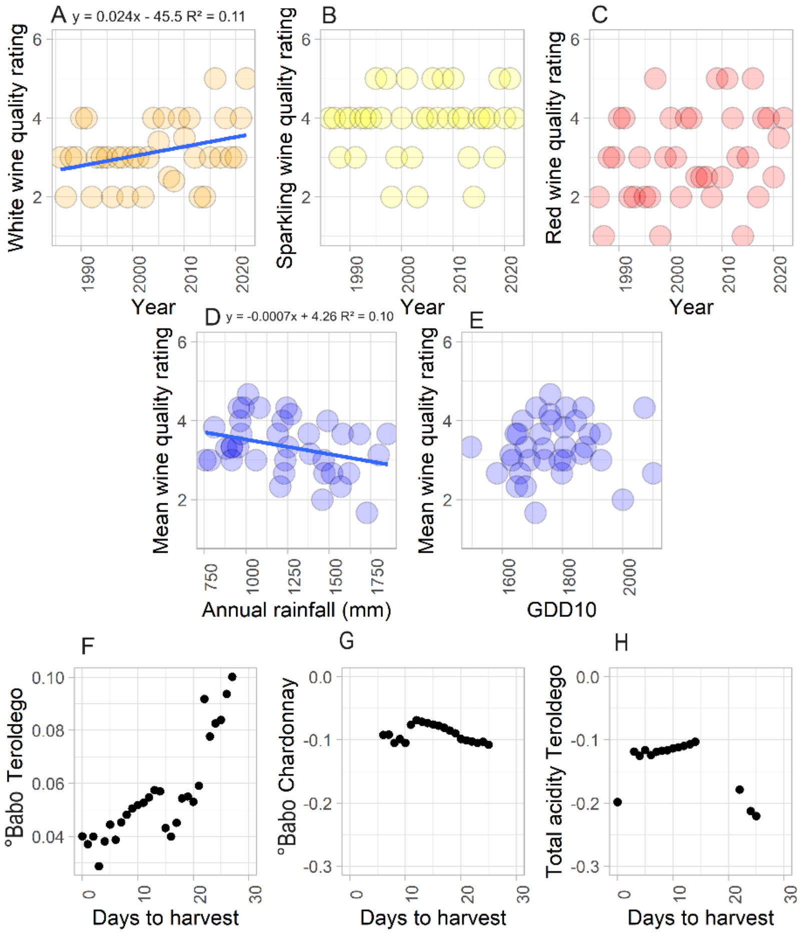

FIGURE 11. A) White, B) sparkling, and C) red vintage quality (internal Mezzacorona Sca rating) over the years. Average quality rating as a function of annual rainfall (D) and GDD$_{10}$. Data were analysed via liner regression and only significant relationships ($p < 0.05$) are shown in the graphs. The linear model equations referring to the relationships between the studied parameters, along with the corresponding R^2 are shown in the graphs and for significant models only. Statistically significant annual trends of °Ba/year for Teroldego (F) and Chardonnay (G), and total acidity (per year, expressed as g/L) for Teroldego (H). Different measurement timepoints are noted in days before harvest on the x axis. Hence, moving from right to left in each graph, the trends refer to days closer to the harvest. It should be noted that there are no significant trends in acidity for Chardonnay (not shown).

The correlation matrix shown in Figure 9 includes the statistically significant correlations between phenological and quality variables and the environmental data of the previous year. There was no correlation between a phenological phase DOY and environmental variables of the summer period for the previous year (1 April to 30 September or 15 May to 15 June; Figure 9). However, an association was observed for a current year in which all the summer thermal variables showed a strong effect on advancing phenological phases (Figure 8). Inverse correlations were observed for soil temperatures of the previous cold season (October to March) and for air temperatures (mainly between April and June of the same growth season) with phenological onsets. Regarding interannual relationships, an increase in De Martonne index corresponded to an advancement of the phenological phases of the following year (Figure 9), but not of the current year (Figure 8). Budburst (BBCH07) was the only phenological phase showing an inverse correlation with the sum of GDD$_{10}$ of the previous year, while all the other phases showed this relationship only with respect to the current year environmental dynamics.

As expected, GDD requirements are all positively correlated with the thermal environmental variables of the same year, especially with mean air temperature and Huglin Index, although GDD also showed some correlations with thermal variables of the previous year (see Figure 10). In addition, the sum of GDD$_{10}$ to reach BBCH07 and BBCH61, the De Martonne index and the mean air temperature of autumn are inversely proportional to total annual evapotranspiration of the previous year for both Teroldego and Chardonnay.

Internal (Mezzacorona Sca) wine rating over years (i.e., over the climatic changes provided above) showed a linear and significant increase ($p < 0.05$) in white wine quality while no trends were observed for sparkling and red wine (Figures 11A, B and C respectively). The overall quality was linearly, negatively and significantly ($p < 0.05$) associated with annual rainfall (Figure 11D), while no overall correlation was observed between quality and GDD_{10} (Figure 11E). Babo grade trends showed specific behaviour (increasing for Teroldego and decreasing for Chardonnay) at every time point before harvest (Figures 11F and 11G). Acidity trends were significant for Teroldego only (Figure 11H) and the Babo grades were similar for different time points before harvest, but slightly higher (about -0.02 grams/year) 22 days before harvest and on the day of harvest itself. Sugar concentrations behave oppositely in Chardonnay and Teroldego during the days preceding harvest: for Teroldego the Babo grade increased from 1986 to 2022 (about +0.05 °Ba/year), while for Chardonnay it decreased (about -0.1 °Ba/year); conversely, only the acidity of Teroldego showed significant trends, with a decrease of about -0.1 g/year.

DISCUSSION

1. Climate change in the Trentino region impacted several agroclimatic indicators and grapevine phenological onset over the last forty years.

In this work, we used a long-term dataset for phenology and specific environmental data to evaluate the climatic tendencies imposed by climate change, as well as the relationships between phenology and quality for two grapevine varieties grown under homogeneous growing conditions and management. An overall and long-term shift in temperatures and weather patterns is widely documented in the literature (Alikadic *et al.*, 2019; Bock *et al.*, 2011; Cameron *et al.*, 2020; Cameron *et al.*, 2021; Cameron *et al.*, 2022; De Cortázar-Atauri *et al.*, 2017; Dinu *et al.*, 2021; Jones *et al.*, 2005; Laget *et al.*, 2008; Tomasi *et al.*, 2011; Xyrafis *et al.*, 2022). In the Trentino basin, we confirm a significant increase in average air temperature, which is estimated to be ~0.1 °C every three years over the last thirty-six years, a similar value to several other studies, such as those of Xyrafis *et al.* (2022) (0.06 °C annual increase for the period 1980-2020 on Santorini Island) and Laget *et al.* (2008) (increase of 1.3 °C for the period 1980-2006 (mean annual increase of 0.06 °C) in the South of France). Jones *et al.* (2005) found that growing season temperatures in several wine regions throughout the world had increased by 1.3 °C on average over the last 50 years, with local peaks greater than 2.5 °C. Indeed, we found that following this trend the mean air temperature had increased in the Trentino region by 2 °C over 40 years. No tendencies were observed for annual and seasonal precipitation, as well as number of days with rainfall higher than 30 and 50 mm, in contrast to several reports in which a trend of decreasing precipitation has been observed in other viticultural regions (Laget *et al.*, 2008; Moreno *et al.*, 2017; Ramos *et al.*, 2008; Xyrafis *et al.*, 2022). In the present study, the observed warming trend has significantly increased evaporative demand, as is the case in many other regions worldwide, suggesting a potential negative effect on water availability during the growing season and overall drought feedback. Similarly, the warming trend has positioned Trentino (at least the valley areas; i.e., Piana Rotaliana) within a higher bioclimatic region of the Winkler index, with 2022 pushing towards Region IV (1600 to up to 2000 GDD on base 10 °C) or "warm" grapevine grouping (16.5 to around 18.5 °C on average during the growing season) (Amerine and Winkler, 1944). These results reflect the repositioning of Santorini Island from Region III to IV as observed by Xyrafis *et al.* (2022), and are in line with the forecast shift in Greek viticultural areas to GDD conditions above the ranges of the Winkler Regions in the RCP8.5 emission scenario (Koufos *et al.*, 2018). The associated exploitation and characterisation of different pedoclimatic conditions for specific oenological aims was not evaluated in the present study, as achieving high-elevation viticulture is still a possibility in the Trentino region, and thus a potential means of keep varietal specificity within the same territory (Alikadic *et al.* 2019). Overall, part of this linear warming was accompanied by an autumn to spring increase in air temperature, which was in turn associated with an overall increase in autumn to winter soil temperature and general increase in annual cumulative radiation. We speculate that the increase in radiation may be explained by a reduction in cloud cover, as well as by changes in aerosol composition (Isaksen *et al.* 2009), and that this trend may have been critical in the phenological advancement shown for both the assessed varieties, for which, on average, the advancement in phenological onset is occurring at a rate of between 0.3 and 0.5 days/year. Similarly, in a study of 29 cultivars in Greece, Koufos *et al.* (2020) identified a harvest advancement trend of 0.76 days/year on average, over a period spanning 1980 to 2017. While the earlier flowering, veraison and harvest time can be explained by a general higher thermal accumulation, higher radiation during the growing season and potential increase in developing water limitation, the advancement in budburst date can be linked to the air/soil warming occurring in winter, thus anticipating ecodormancy release. Early budburst is an ongoing issue in viticulture (Poni *et al.*, 2022; Faralli *et al.*, 2024), and northern Italy has historically suffered from winter vine survival rather than post-budburst freezing damages. Climate change is significantly pushing the budburst day to last freezing day subtraction towards negative values, thus increasing the possibilities of late frost occurrence on young and fragile shoots. This observation agrees with a series of phenological modelling studies, which predict - albeit with degrees of uncertainty - an increase in late frost risk in many viticultural areas under future climate scenarios (Kartschall *et al.*, 2015; Leolini *et al.*, 2018; Meier *et al.*, 2018; Mosedale *et al.*, 2015; Sgubin *et al.*, 2018). Our work suggests that at this climatic rate, and for Chardonnay (a variety that undergoes relatively early budburst), there will be an increase in the possibility of frost damages, based on two specific environmental dynamics: i) higher winter-to-spring thermal accumulation, in any case associated with lower number of total days with temperatures below 0 °C, and ii) the unchanged timing of the last day on which late frost occurs - between 75 and 120 DOY on average. Therefore, higher temperatures shift phenology and the post-veraison period into seasonal cycles that represent a challenge for the production of quality wine, and thus typicity maintenance, with potential negative effects on productivity (late frost damages, potential lowered bud differentiation, lower must yield): our work indeed shows evidence of these dynamics. As is the case in many other viticultural areas, short-term adaptation strategies are also required in the northern Italian basin.

2. Phenological interphases are only partially compressed by climate change

It is still a matter of debate whether phenological compression or shifted vegetative growing season are the main drivers of the overall changes in phenological timing observed in the many studies (Cameron *et al.*, 2020; Cameron *et al.*, 2021; Cameron *et al.*, 2022; De Cortázar-Atauri *et al.*, 2017; Dinu *et al.*, 2021; Jones *et al.*, 2005; Laget *et al.*, 2008; Tomasi *et al.*, 2011; Xyrafis *et al.*, 2022) included in the present work. Different pedoclimatic conditions, varieties, rootstocks, crop load, row orientation and general management practices may explain part of the variation observed in several studies, with contrasting conclusions regarding interphase dynamics. However, we observed a general advancing trend for flowering to harvest interval length in both varieties. The advancement was more pronounced for Chardonnay (0.18 days/year) than Teroldego, although this cannot explain the larger advancement in harvest date. Assuming that harvest cannot be classified as a phenological growth stage (Menzel *et al.*, 2006a; Menzel *et al.*, 2006b), our work defines an advancement in the only interval length for which the end point (i.e., harvest) is defined by a complex and often indefinable feedback interaction between thermal accumulation, timing of the phenological onset (in this case, onset of flowering) and oenological aim (Cameron *et al.,* 2022). While this observation will be examined in the last section of the discussion, it indicates that we were unable to detect a trend for the compression of any actual phenological interphase length, in contrast to, for example, Cameron *et al.* (2022). However, the association between BBCH07 DOY and BBCH07 to BBCH61 interval length suggests that, overall, as a result of early budburst, the subsequent interphase will experience higher probability of cooler periods, hence reducing the time to unlock flowering. Indeed, this has already been observed by Cameron *et al.* (2022), who detected a curvilinear response between phase length (budburst to flowering) and thermal accumulation and found that for most of the tested varieties lower average temperatures produced an extended interphase. Indeed, Cameron *et al.* (2022), found the budburst to flowering interphase to have the highest slope with increasing average air temperature, hence suggesting a significant interval-length plasticity to environmental conditions. Another factor, which is less dependent than temperature on year-to-year variability, is the photoperiod. A variation in budburst onset between DOY 90 and 110 equates to a daylight length differing by almost one hour (at the Northern Italy latitude), which inevitably impacts daily photosynthetic CO_2 uptake by the growing autotroph shoot. If early budburst means longer time to reach flowering, late veraison - potentially for similar reasons - means longer interval length between veraison and harvest. Although inevitably associated with the dynamics of berry quality, this data corroborates and strengthens those studies aiming at postponing ripening to colder periods (Böttcher *et al.*, 2022). In our work, delaying veraison from late July to mid-August extended the veraison to harvest interval length by 15 days potentially due to i) lower thermal accumulation post-veraison, and ii) reduced daily photoperiod. Taken together, our work provides evidence of a minimal effect of climate change on phenological interval length, as early onset of a given growth stage shifts the subsequent growth period towards environmental conditions less (budburst) or more (veraison) favourable for vine growth.

3. Dynamic effects of previous seasons on phenological onset and growing degree days required to unlock a phenological phase: can climate change impose an additive effect on phenology over years?

Inter-annual effects have been shown to be common in perennial tree crops with long-term responses that include several structural changes at the organ, tissue, and cellular levels (De Micco and Aronne, 2012; Kim *et al.*, 2007; Neumann, 1995; Von Arx *et al.*, 2012; Zait *et al.*, 2019). For instance, it has been shown that a perennial water-stress memory response exists in *Vitis vinifera,* and that this influences petiole structure at the beginning of the following season (Shtein *et al.*, 2021). Regulating water availability during the period of stem cambial activity intra-annually could be a means for viticulturists to influence water status and determine wine quality by manipulating xylem structure (Netzer *et al.*, 2019). Recent work has also provided evidence of carbon availability mechanisms under high temperature conditions that influence bud flower differentiation and hence following year productivity (Tombesi *et al.*, 2022), as well as an endo-to-ecodormancy transition leading to earlier budbreak following previous year water limitation (Shellie *et al.*, 2018). Although in some cases the mechanisms behind the inter-annual environmental effects remain elusive, part of these trends were confirmed by our analysis. Of interest from a viticultural point of view, there was a trend of reduced GDD_{10} requirements for unlocking early phenological events, particularly BBCH07. Along with the winter-to-spring warming and the non-significant trend for the last day of frost, these data are associated with further issues surrounding late frost. One direct explanation of this may be attributed to the tight association between cold hardiness, dormancy depth and de-acclimation rates under low-to-high temperature transition that may affect time of budbreak. Recently, North and Kovalesky (2024) suggested the inclusion of cold hardiness evaluation to better assess and model budbreak in different species, as cold hardiness depth was affecting time to budbreak after a longer time to lose supercooling ability. Since cold hardiness is driven by low-temperature exposure, increase in autumn-winter temperatures observed in our work over the last forty years may have weakened the cold hardiness state and therefore speeded up bud de-acclimation; i.e., the removal of the supercooling state necessary for budbreak. The negative correlation between BBCH07 and winter temperature corroborates this hypothesis. Moreover, endodormancy release (hence cold hardiness build up) is governed by abscisic acid. Short-day photoperiod regulates the onset of endodormancy via *in situ* biosynthesis of abscisic acid (ABA) in the buds, and the abundance of this phytohormone is associated with endodormancy depth (Pérez and Rubio, 2022; Rubio *et al.*, 2016; Rubio *et al.*, 2019b; Rubio *et al.*, 2019a). Further, ABA release happens after the fulfillment of chilling requirement and a consequent upregulation of ABA catabolism (Dantas *et al.*, 2020; Parada *et al.*, 2016; Pérez and Rubio, 2022; Rubio *et al.*, 2016, 2019b, 2019a; Rubio and Pérez, 2019; Vergara *et al.*, 2017). However, Shellie *et al.* (2018) highlighted a drought stress-induced regulatory network that interacts with environmental and hormonal regulatory signals, mainly leading to an earlier budbreak. These data are in contradiction to the expected ABA-induced dormancy effect, as a deep endodormancy induction should be expected following a severe water stress event driving ABA biosynthesis and accumulation. However, the data are in line with our long-term analysis, in which the lower GDD_{10} required to reach BBCH07 (accelerating budburst) was associated with increased average annual temperature, the GDD_{10} of the previous year and the De Martonne index. Our data provide further indication, supported by the findings of Shellie *et al.* (2018), of possible additive effects of stressful environmental conditions in the previous year on thermal response and phenological onset, raising additional concerns on phenological advancements. The mechanisms behind this trend should be further dissected.

4. Early harvest is a strategy for maintaining must acidity in white berry varieties, while harvest time is dictated by the temperature to rainfall ratio in red berry varieties.

The harvest date for grapevine is rarely dictated by ripening *per se*, as the interaction between several technological parameters defines the optimal harvest time point for the chosen oenological aim. Evidence of the decisional bias associated with harvest date compared to other phenological observations have been provided (van Leeuwen and Darriet, 2016). While in i) northern and south-west France (e.g., Alsace and Bordeaux respectively) growers take advantage of warmer conditions to harvest at greater levels of ripeness, in ii) Mediterranean-like viticulture in France and in Mediterranean viticulture in Greece, increasing ripeness levels is not an oenological target. Therefore, in the second case the advancement in harvest date is much more prominent than in the first. However, tipping points for specific oenological targets have been observed at increasing ripening progressions or average temperatures, such as for anthocyanins (Gambetta and Kurtural, 2021), suggesting potential future harvest advancement with climate change, even at higher latitudes. In our case, the oenological aims of the two varieties differed, as expected. Indeed, for Chardonnay, the harvest date was always chosen by setting the same acidity target (which in fact shows no variations), even when it means a reduction in sugar content. This is in line with the fact that in white/sparkling wine the Brix/acidity ratio of the juice is a determinant (Jones *et al.*, 2014), as well as with phenological advancement and shorter flowering to harvest interval length. However, while white wine quality (according to the internal winery rating) has improved over years, no effect has been observed for sparkling wine quality, which shows an inverse correlation with the number of days exceeding 35 °C. This data provides evidence of potential further negative effects of climate change, mainly via a de-coupling of malic acid degradation (faster) and sugar accumulation (slower at high temperature) (Palliotti *et al.*, 2014), thus potentially affecting the quality of berries used for sparkling wine, even in the foreseeable future. In Teroldego, we observed a reduction in juice acidity and a slight increase in sugar content over the years, with no apparent negative impacts on wine quality. However, quality was positively correlated with total evapotranspiration and maximum annual temperatures, suggesting a generally positive role (Jones and Davis, 2000) of warming trends for red berry varieties in the Trentino basin. In addition, the total rainfall values were directly proportional to the periods between bud and veraison and between flowering and veraison, but inversely proportional to the time between veraison and harvest. Therefore, it is very likely that early harvest in Teroldego was associated with post-veraison rainfall rather than with warming (that enhanced some chemical parameters of the berry). The bunch-zone microclimate, in particular humidity (Tello and Ibáñez, 2018), is an important factor that defines berry sanitary status, and high precipitation before harvest may increase the occurrence of botrytis (cold) or acid rot (warm), which was possibly minimised in Teroldego as a result of the early harvest. Our work provides evidence of the complex interplay between climate change, variety, and oenological aims, which, according to our data, have been well managed by viticulturists to avoid loss of wine quality and typicity. Although speculative at this stage, the expected further changes in climatic conditions could additionally affect viticulture to such an extent that management and harvest date decisions will unlikely be effective, thus warranting further work on future adaptation strategies.

CONCLUSIONS

We showed that between 1986 and 2022 in the northern Italian region of Trentino mean air temperature increased by ~ 0.1 °C every three years. Several agroclimatic indices, particularly the Growing degree days and Huglin Index, served as reliable indicators of such dynamics, corroborating previous studies on this topic carried out for other viticultural regions worldwide. Consistent with other studies, climate change resulted in a significant advancement (by up to 20 to 30 days) in the onset of phenological stages in both white and red berry varieties during the analysed period; meanwhile, a substantial equilibrium in the seasonal growing length over the years was maintained due to the phenology-heat accumulation relationship. We found evidence of additive effects on phenological onset resulting from stressful environmental conditions in preceding seasons and associated with thermal units required to unlock budburst therefore increasing the probability of late frost damages. However, the quality of white wine improved over the years, while red and sparkling wines remained unaffected, possibly due to the precise determination of harvest dates based on berry quality parameters; specifically, the sugar-to-acidity ratio dictated the harvest date for Chardonnay, while the sanitary status determined the harvest date for Teroldego. This study highlights the dynamics involved in climate change and, to our knowledge, its overlooked effects on viticulture, thus providing new information that can contribute to further developing adaptation strategies.

ACKNOWLEDGEMENTS

The work was supported by internal funding from University of Trento awarded to MF and MB.

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