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ORIGINAL RESEARCH ARTICLE

The interplay between grape ripening and weather anomalies in Northern Italy – A modelling exercise

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ABSTRACT

Current climate change is increasing inter- and intra-annual variability in atmospheric conditions leading to grapevine phenological shifts as well as altered grape ripening and composition at ripeness. This study aims to i) detect weather anomalies within a long-term time series, ii) model grape ripening revealing altered traits in time to target specific ripeness thresholds for four *Vitis vinifera* cultivars, and iii) establish empirical relationships between ripening and weather anomalies with forecasting purposes. The Day of the Year (DOY) to reach specific grape ripeness targets was determined from time series of sugar concentrations, total acidity and pH collected from a private company in the period 2009–2021 in North-Eastern Italy. Non-linear regression models were fitted over a time series of ripening parameters on a calendar time basis and assessed for modelling efficiency (EF) and error of prediction (RMSE) in four grapevine cultivars (Merlot, Cabernet-Sauvignon, Glera and Garganega). For each vintage and cultivar, advances or delays in DOY to target specified ripeness thresholds were assessed with respect to the average ripening dynamics. A thirteen years' long meteorological series monitored at a ground weather station using hourly air temperature and rainfall data was analysed. Climate statistics were obtained and for each time interval (month, bimester) weather anomalies were identified. A linear regression analysis was performed to assess correlations between ripening and weather anomalies. For each cultivar, ripeness advances or delays expressed in the number of days to target the specific ripening threshold were assessed in relation to registered weather anomalies and the specific reference time interval in the vintage. Precipitation of the warmest month and temperature anomalies during late spring (May–June) and during the warmest month (August) we found to be important to understanding the effect of climate change on sugar ripeness. Maximum and minimum temperatures of the May–June bimester and maximum temperatures of the warmest month best correlate with altered total acidity evolution and pH increment during the ripening process. A new modelling framework is presented using historical data that supports management decisions by better understanding past impacts and forecasting for the future.

KEYWORDS: temperature, rainfall, berry composition, grapevine ripening, sugar, acidity, climate change, Glera, Cabernet-Sauvignon, Merlot, Garganega

INTRODUCTION

Viticulture is one of the most widespread agricultural production systems in the world, representing a global multibillion-dollar enterprise (OIV., 2019). Wine production results from complex interactions between the physical environment (climate, soil), the cultivar and cultivation techniques, which finally determine the *terroir* concept (van Leeuwen *et al.*, 2004; van Leeuwen and Seguin, 2006). Local viticulture aims at adapting vineyards and wine models to the available natural resources that best suit the site and the chosen wine objective (Jones *et al.*, 2012). Viticultural regions are located in relatively narrow geographical and climatic ranges, and, in addition, large cultivar differences exist in climate suitability. These narrow "niches" for optimum quality and production put the grapes' cultivation at greater risk from both short-term climate variability and long-term climate changes than other crops (Dai *et al.*, 2011; Dalla Marta *et al.*, 2010; Jones, 2015; Jones and Davis, 2000; Jones *et al.*, 2012; Kenny and Harrison, 2007; Sadras *et al.*, 2007; Schultz and Hofmann, 2015).

Climate regulates not only the geographical distribution but also the quality of vine cultivation. When other terroir factors are held comparatively constant, climate feasibly exerts the strongest effect on the suitability of a region or a site to produce quality grapes and significantly modulates grape berry composition during ripening to confer optimum characteristics to a given wine style (Ashenfelter and Storchmann, 2014; Jones and Davis, 2000; Makra *et al.*, 2009; Zoecklein and Gump, 2022).

In general, the climate of a given region overall determines to a great extent the most suitable grape cultivars and their wine styles, while wine production and vintage quality differences are principally influenced by site-specific factors, management practices and short-term climate variability (Jackson and Lombard, 1993; Keller, 2010; Naulleau *et al.*, 2020). Current climate change factors and their potential impacts on wine production have become increasingly important as the Earth system undergoes increased levels of greenhouse gases and land use alterations, leading to changes in the Earth's radiation budget, atmospheric circulation, and hydrologic cycle (Shukla *et al.*, 2019). According to IPCC, during the past decade, unprecedented high-impact climate extremes, including droughts, heat waves and floods, have occurred in all parts of the world (Shukla *et al.*, 2019). Under future climate change scenarios, traditional wine-growing regions, where terroir expression has been optimised through millenary experience, will likely face more frequent and intense extreme weather events (Templ *et al.*, 2021). Vintage to vintage production and quality variations are likely to become much greater throughout the world, impacting typicity and economic outcomes. Both a changing climate and greater seasonal variability will likely influence fruit set and affect maturity, crop uniformity, and maturity evaluation (Zoecklein and Gump, 2022).

Extensive literature references exist on climate change impacts on viticulture and future global wine production (Hannah *et al.*, 2013; Morales-Castilla *et al.*, 2020; Moriondo *et al.*, 2013; Santillán *et al.*, 2019; Santos *et al.*, 2012; van Leeuwen *et al.*, 2013). The impacts of climate change are not likely to be uniform across all cultivars and wine regions but are more likely to be related to climatic thresholds whereby any continued warming would push a region outside the ability to produce quality wine with existing cultivars (Jones and Alves, 2012). According to much of the international scientific community, viticulture in Europe is moving further and further north because of the climate change taking place. Some northern European countries could take advantage of this climate change scenario and new wine-growing regions would appear where it was previously not possible viticulture due to limiting climatic conditions. At the same time, in the countries of southern Europe, producers are experiencing serious difficulties in interpreting the season in the best possible way to maintain the high-quality standards required by the market and, at the same time, best express the terroir itself (Ausseil *et al.*, 2021; Duchêne and Schneider, 2005; Santos *et al.*, 2021).

After véraison, the grape berry is subject to a series of coordinated chemical and metabolic changes of considerable magnitude (Kuhn *et al.*, 2014). The phenomenon of maturation is a very fascinating aspect of physiology, but there is still much to understand about the effects of climatic variables and their interactions on the multiple, complex, and often non-linear transformations that affect the berry. Temperature controls vine growth (Meggio and Pitacco, 2019; van Leeuwen *et al.*, 2004), phenology and vine's rate and thresholds of physiological development, but it is also one of the main factors that affect the process of evapotranspiration. If the increase in the intensity of the transpiration process is supported by sufficient water availability, the maturation dynamics will be accelerated. Growing season length and average temperatures are critical because of their major influence on grape ripening and fruit quality and, therefore, cultivar adaptation to specific regions. It is in its ideal climates that a given cultivar can achieve the best ripening profiles to optimise a given style of wine and vintage quality.

The increase in temperatures caused by climate change will likely affect many of the biological and physiological processes of living organisms. Many regions have experienced increasing sugar concentrations, resulting in increasing potential alcohol of 1–2 %, significantly impacting wine balance (Bécart *et al.*, 2022). The consistent results of analysis of global phenology trends and different quality and quantity variables were reported in a recent study conducted by Bécart *et al.* (2022) on cv. Grenache in the Rhône Valley (France) on different maturity and yield variables over the last 50 years confirms results obtained in previous studies in other vineyards around the world (Duchêne and Schneider, 2005; García de Cortázar-Atauri *et al.*, 2017; Jones and Davis, 2000; Mavromatis *et al.*, 2020; Neethling *et al.*, 2012; Petrie and Sadras, 2008; Ramos *et al.*, 2015). It shows that all phenological stages of grapevines moved earlier than 50 years ago (from 10 to 20 days depending on the phenological stage, the location and the cultivar), resulting in a shift of the maturation phase to warmer parts of the summer (Bécart *et al.*, 2022).

Considering warmer conditions due to a changing climate, Greer and Weston (2010) subjected berries at different physiological development stages to high thermal regimes for relatively long time periods: 40 °C during the day and 25 °C at night for four days. The varietal response was not clear-cut, but in general, the berries that underwent this heat treatment at the fruit set stage showed substantial regular growth characteristics, while those that were affected by the same treatment in the véraison and post-véraison phase stopped their development at the time of treatment. As for the accumulation of sugars, the imposed conditions showed a temporary arrest of about a week and later resumed growth, reaching high levels (25–27° Brix) and then decreasing. The inhibition of the accumulation of sugars due to the administration of heat in the Greer and Weston (2010) research can be attributed to the restriction of the phloematic load inside the berry, to the reduced transport of sugars or to the reduction of the supply by the "source" organs.

Temperature also exerts a considerable influence on the organic acid evolutions in the grape berries, in particular on malic acid (Ruffner *et al.*, 1976), where in colder regions, fruits with a higher concentration of malic are produced, while regions with higher thermal regimes produce grapes with a low acidity content. Some of the strongest and most consistent negative relationships between titratable acidity in the berry and temperature are related to maximum temperatures (Barnuud *et al.*, 2014). This negative correlation between malic acid levels and temperature is due to the effect that temperature itself exerts on the synthesis and catabolism of malic acid (Conde *et al.*, 2007). In general, respiration of tartaric and malic acids increases with increasing temperatures, leading to an acceleration in the decreases of titratable acidity and increases in pH (Buttrose *et al.*, 1971; Ruffner *et al.*, 1976).

Given its importance to overall vine balance, grape quality, yield, and disease pressure, understanding the water relationships in any wine region is critical. Atmospheric humidity is very important in affecting the environmental demand for evapotranspiration and the occurrence of fungal diseases. Rainfall is critical to the vineyard's water balance; however, intense and persistent precipitation can impact vineyards by leading to the run-off of nutrients and water on the soil surface while causing soil losses by erosion. Controlled water supplies through irrigation applied at the right times during growth and ripening can enhance quality and control yield. Castellarin *et al.* (2007) attempted to induce water stress conditions in grapevines, both before and after véraison. Stress in the pre-véraison phase caused an acceleration of the process of sugar accumulation and anthocyanin synthesis, and both stresses led to an increase in the accumulation of anthocyanins after véraison. A Portuguese study (Santos *et al.*, 2003) has also shown that water stress leads to the better composition of the bunches and wine as it leads to lower development of the foliage allowing a greater possibility of interception of light in the area of the bunches. While Ruffner *et al.* (1976) found that irrigation, potassium level and production level do not affect the rate of increase in berry weight while the content of soluble solids decreases with increasing irrigation (for a kind of dilution), total acidity has also been observed to decrease due to dilution of acids caused by incremental increases in berry sizes (Barnuud *et al.*, 2014; Costa *et al.*, 2020; Costa *et al.*, 2019; López *et al.*, 2007).

There has been extensive literature focusing on climate change impacts on grape ripening and future global wine production. The body of research points to an urgent need for the development of mechanistic models that allow a deeper understanding of the complex dynamics that relate to all the factors involved in plant growth and development (Dai *et al.*, 2009; Moriondo *et al.*, 2015). As such, the development of empirical models to explore climate influences on berry growth and development, acknowledging their limitations, represents a powerful tool for today and for the future.

The present study takes aim at part of this challenge by seeking to build an innovative modelling framework and, at the same time, provide an intuitive tool to allow a better understanding of the future climate change scenarios through an in-depth characterisation of the past. A database was created which integrates data from maturation dynamics data since 2009 on four grapevine cultivars of both national (Italian) and international interest: Cabernet-Sauvignon, Merlot, Glera and Garganega. The study aims to i) examine weather and ripening anomalies within a 13-year time period, ii) model grape ripening traits over time to specific target ripeness thresholds for four *Vitis vinifera* cultivars and iii) establish empirical relationships between ripening and weather anomalies as decision support algorithms for backward agronomic assessments and future impact forecasts. Finally, the study sought to contribute to the understanding of climate change impacts on vineyards in Northeast Italy.

MATERIALS AND METHODS

1. Monitoring sites, plant material and climate data

Sixteen commercial vineyards within the district of the 'Colli Berici' wine region (Figure 1) were used to monitor the dynamics of total soluble solids (TSS), titratable acidity (TA) and pH in four *Vitis vinifera* L. cultivars: Cabernet-Sauvignon (CS), Merlot (ME), Garganega (GA) and Glera (GL). Monitoring was carried out from véraison until harvest during the 2009–2021 growing seasons. The 16 study vineyards lie within the municipality of Lonigo in the province of Vicenza, in northeast Italy (Table 1, Figure 1). The different sites are located within an area of approximately 5 km^2 with elevations ranging from 28 to 152 m asl. Plant age varied widely, from 15 to more than 60 years, with a mean yield per hectare of 15 tons (CS), 20.7 (ME), 25 (GA) and 14.5 (GL).

Historical records were monitored at the weather station of 'Lonigo' (45.391N, 11.379E, 21 m asl) of the Regional

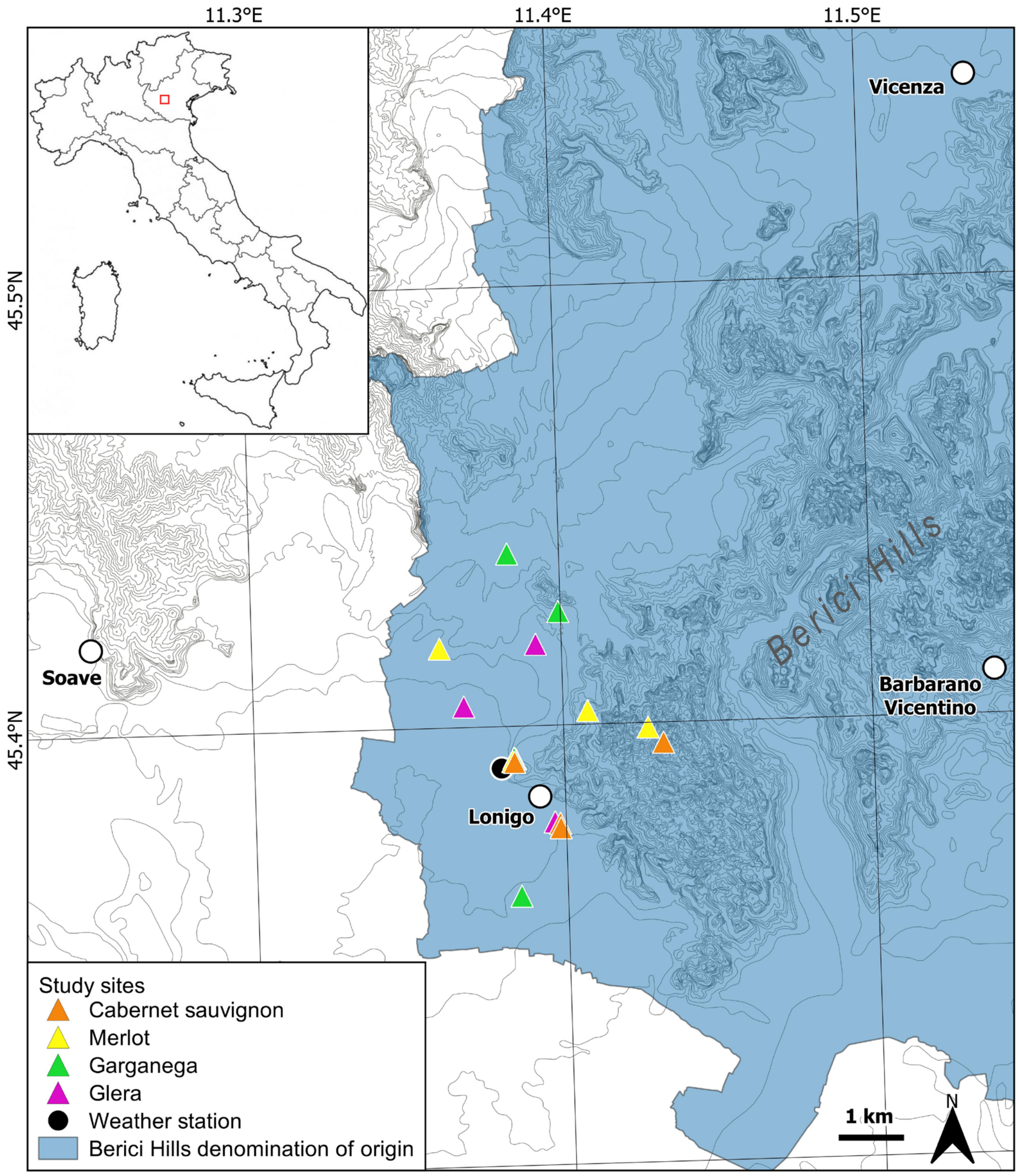

FIGURE 1. Map of the study area in the Berici Hills denomination of origin, Northeast Italy. Study site locations are represented by triangles (according to a specific cultivar colour) and the white circle represents the weather station of the Regional Agency for Environmental Protection (ARPAV).

Agency for Environmental Prevention and Protection (ARPA Veneto) by means of hourly air temperature (measured at 2 m from the ground) and rainfall data were obtained for the period 2009–2021. The full year of data was obtained, and the arithmetic mean, minimum (T_{min}) and maximum (T_{max}) temperatures and precipitation totals (P_{sum}) were calculated for each day (following the WMO's international standards).

The climate means for each time interval (month, bimester) for T_{min}, T_{max} and P_{sum} were obtained for the period 2009–2021. For each climate indicator, weather anomalies were computed as deviations from the average time period (2009–2021). Temperature and precipitation for the Lonigo site over the average time period of 2009–2021 (period in which maturation data were available for study) were used. The study area has a temperate subcontinental climate characterised by relatively harsh winters and hot summers (Figure 2A). Precipitation is distributed evenly throughout the year and with annual totals on average of about 815 mm, with winter as the driest season. Precipitation totals (P_{sum}) show a two-peak behaviour in May and November with mean values of about 98 and 95 mm, respectively. January and December resulted in the lowest rainy months with values of 50 mm and 55 mm, respectively, followed by July (59 mm). The average (2009–2021) for maximum (T_{max}) and minimum (T_{min}) temperatures was 19.2 °C and 10 °C, respectively, resulting in a mean temperature of 14.4 °C.

In this study, the influences of climate variables on berry composition were examined throughout the same time interval (2009–2021). Ten sites used vertical shoot positioning (VSP), five with a double 'Capovolto' or bi-lateral cane pruning

TABLE 1. Cultivar, geographical coordinates, elevation, vine ages, training systems and average yields for the study sites. Data were provided by the agricultural consortium of cooperatives Collis Veneto Wine Group.

id	Cv.	GPS coordinates (Lat, Long)	Elevation (m asl)	Age (years at 2021)	Planting density (vines/ha)	Training system	Mean yield (tons/ha)
1	CS	45.395N, 11.432S	152	29	2778	VSP, double 'Capovolto'	8
2	CS	45.390N, 11.377S	28	15	4000	VSP, spur	12
3	CS	45.378N, 11.401S	26	16	3367	VSP, double 'Capovolto'	15
4	CS	45.378N, 11.401S	26	16	2849	VSP, double 'Capovolto'	10
5	ME	45.399N, 11.429S	141	17	4167	VSP, double 'Capovolto'	12
6	ME	45.418N, 11.361S	33	17	4348	VSP, spur	25
7	ME	45.390N, 11.377S	28	15	4167	GDC	25
8	ME	45.405N, 11.369S	56	19	4348	VSP, spur	18
9	GA	45.426N, 11.399S	39	46	2083	Pergola Veronese	25
10	GA	45.362N, 11.384S	25	61	2500	Pergola Veronese	25
11	GA	45.439N, 11.383S	42	35	2500	Pergola Veronese	30
12	GA	45.390N, 11.377S	28	15	4348	GDC	20
13	GL	45.405N, 11.395S	138	16	4000	VSP, bi-lateral	10
14	GL	45.378N, 11.401S	26	15	3367	VSP, double 'Capovolto'	15
15	GL	45.419N, 11.391S	34	15	3571	VSP, Sylvoz	18
16	GL	45.390N, 11.377S	28	15	4167	GDC	15

*CS Cabernet-Sauvignon, ME Merlot, GA Garganega, GL Glera, VSP Vertical shoot positioning, GDG Geneve Double Curtain.

method, three with spur pruning and one each with sylvoz and bi-lateral pruning. Three sites used Geneve Double Curtain (GDC), while three GA sites were trained as 'pergola veronese'. All vineyards were equipped with drip irrigation systems, but their use is strictly regulated and allowed only upon critical drought or heat waves conditions occurring. From this point of view, all the different study vineyards were under the agronomical control of the technician personnel of the Collis Veneto Wine Group. Regarding the harvest date decision, the ripening dynamics were centrally monitored by the personnel of the consortium upon reaching a target TSS value, thus limiting sources of variations (Table 1).

2. Bunch sampling and berry composition analysis

Ten vines were selected randomly from four rows in the middle of the vineyard to avoid edge effects and multiple sampling on the same vines during the sampling period. Ten bunches of grapes from each vine, five from the side exposed to the sun and five from the shaded side of the canopies, were randomly sampled manually for each cultivar at regular intervals (4–5) between the start of véraison and harvest. Sampled bunches were placed in a chilled box and taken to the laboratory of the Collis Veneto Wine Group for berry sampling and composition analysis. A sample of 100 berries was sampled randomly from the top to the tip of each bunch. Juice from the samples was extracted using a roller crusher and analyses of grape berry quality parameters commonly selected for maturation control (TSS, TA, pH) were performed using a FOSS WineScan FT120 (FOSS, Hillerød, Denmark). The calibration of the WineScan was checked daily against a hydrometer with a temperature correction.

3. Modelling analysis of ripening curves

For each time series (year × cultivar combination), ripening curves expressed as increments of total soluble solids (TSS, g/L) and pH and total acidity (TA, g/L) decreases were modelled using non-linear functions on a calendar time basis (day of the year, DOY) (Sigmaplot version 12; Jandel Scientific Software, San Rafael, CA) minimising the sum of the squares of the differences between the predicted and measured values. Best non-linear functions were selected based on a preliminary analysis of the structure of the data (*data not shown*). Time series of TSS and pH increments were modelled using a three-parameter logistic function of the form:

$$(1) \qquad y = \frac{a}{1+\left(\frac{x}{X_0}\right)^b}$$

where a represents the upper asymptote and, in this case, is the theoretical maximum TSS content and pH value, X_0 is associated with the point of symmetry of the sigmoid (inflection point) and, in this case, is the number of days required to reach 50 % of a, and b is a curvature parameter related to the slope of the curve.

Total acidity (TA) decreases as simultaneous exponential decay of malic acid occurs over time, were modelled using a two-parameter exponential function of the form:

(2) $$y = a \cdot x^{-b}$$

where a represents an initial value (positive) raised to a constant exponent b which, if b<0, it represents a factor of decay as x (DOY).

For each time series, model agreement (i.e., the deviation between estimates and observations) was assessed using the coefficient of determination (R^2); a measure to quantify the square difference between estimates and measurements, represented by the root mean square error (*RMSE*, Eq. 3) and its relative form (RRMSE, Eq. 4) and the modelling efficiency (*EF*, Eq. 5) of the form:

(3) $$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{n}}$$

(4) $$RRMSE = \left[\frac{\sqrt{\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{n}}}{\bar{O}}\right] \cdot 100$$

(5) $$EF = 1 - \left[\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right]$$

where E_i is the estimated value, O_i is the observed value, $\bar{O}$ is the mean of the observed values, i is each of the E_i/O_i pairs and n is the number of E_i/O_i pairs.

4. Ripening anomalies definition

For each cultivar, the mean ripening curve over the period 2009–2021 (same as climate data) was also fitted on a calendar time basis representing the mean ripening dynamic expressed as TSS and pH increments and TA decreases at Lonigo viticultural district (Figure 1). For each time series (year × cultivar × ripening parameter) and for the mean time series (cultivar × ripening parameter across years), the day of the year (DOY) to reach 18 specified target ripeness thresholds (Table 2) was determined by each model as proposed for TSS by Parker *et al.* (2020). As the four grapevine cultivars examined exhibited contrasting berry composition levels at maturity and ripening earliness, different thresholds for TSS, TA and pH were defined and considered to carefully sample for each cultivar the real evolution of the ripening process. For each ripening variable, the average value at harvest, considering the mean 2009–2021 time interval, was considered as the upper 18th threshold; the remaining 17 thresholds were selected of equal width from the upper one for all cultivars accordingly (Figures 1–3SM). This procedure allowed to standardise further regression analysis by guaranteeing to get 13 values of ripening anomaly (days in advance or delays against average) for all the 18 thresholds. For each time series (year × cultivar), advances or delays in DOY to target each specified ripeness threshold were assessed with respect to the average ripening dynamics (2009–2021).

TABLE 2. Specified target ripeness thresholds for each cultivar and ripening parameter.

Parameter	TSS (g/L)				TA (g/L)				pH			
Cultivar	GA	GL	CS	ME	GA	GL	CS	ME	GA	GL	CS	ME
1	75	90	125	140	22	22	22	22	2.44	2.48	2.64	2.72
2	80	95	130	145	21	21	21	21	2.48	2.52	2.68	2.76
3	85	100	135	150	20	20	20	20	2.52	2.56	2.72	2.80
4	90	105	140	155	19	19	19	19	2.56	2.60	2.76	2.84
5	95	110	145	160	18	18	18	18	2.60	2.64	2.80	2.88
6	100	115	150	165	17	17	17	17	2.64	2.68	2.84	2.92
7	105	120	155	170	16	16	16	16	2.68	2.72	2.88	2.96
8	110	125	160	175	15	15	15	15	2.72	2.76	2.92	3.00
9	115	130	165	180	14	14	14	14	2.76	2.80	2.96	3.04
10	120	135	170	185	13	13	13	13	2.80	2.84	3.00	3.08
11	125	140	175	190	12	12	12	12	2.84	2.88	3.04	3.12
12	130	145	180	195	11	11	11	11	2.88	2.92	3.08	3.16
13	135	150	185	200	10	10	10	10	2.92	2.96	3.12	3.20
14	140	155	190	205	9	9	9	9	2.96	3.00	3.16	3.24
15	145	160	195	210	8	8	8	8	3.00	3.04	3.20	3.28
16	150	165	200	215	7	7	7	7	3.04	3.08	3.24	3.32
17	155	170	205	220	6	6	6	6	3.08	3.12	3.28	3.36
18	160	175	210	225	5	5	5	5	3.12	3.16	3.32	3.40

*CS Cabernet-Sauvignon, ME Merlot, GA Garganega, GL Glera, TSS total soluble solids, TA total acidity. See Figures 1–3SM.

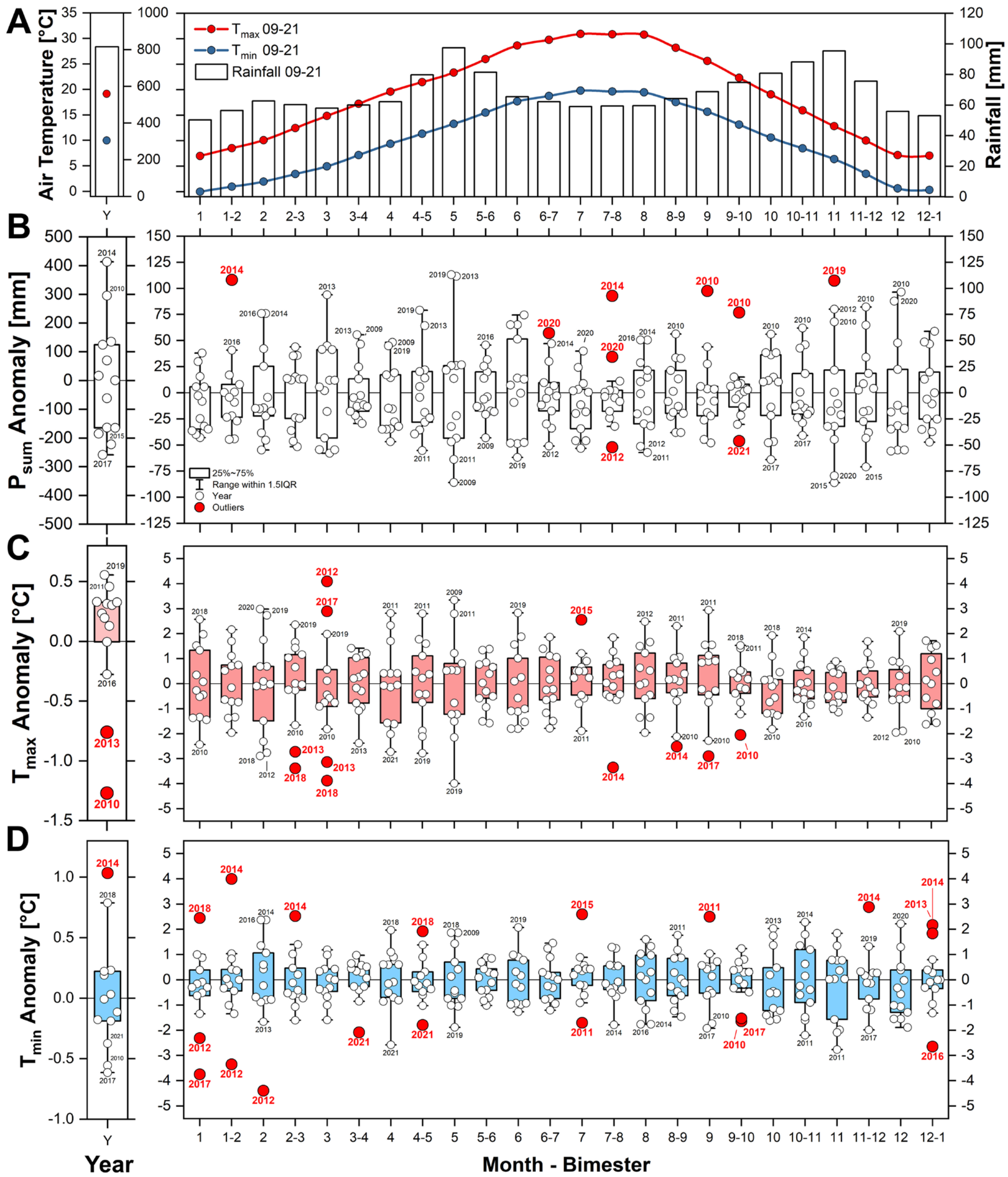

FIGURE 2. (A) Climograph showing monthly (n), bimester (n-n) or annual (Y) characteristics for maximum (T_{max}, red line) and minimum (T_{min}, blue line) air temperature and precipitation totals (P_{SUM}, white bars) for different time intervals: annual (Y), monthly (n) and bimester (n-n). Box plots show the distribution of the climate anomalies (empty circles) against the 2009–2021 average time period for P_{sum} (B), T_{max} (C) and T_{min} (D). Each box delimits 25 and 75 % quantiles and whiskers are drawn from the 1.5 IQR value. The red circles are outlier values, i.e., anomalous years.

5. Development of relationships of ripening-to-climate anomalies

A linear regression analysis was performed to assess possible correlations that may exist between berry ripening dynamics and weather anomalies. For each cultivar and each specified target ripening threshold for berry quality parameters (TSS, TA, pH), ripeness advance or delay expressed as the number of days to target the specific ripening threshold (Table 2) were assessed in relation to registered weather anomalies within each given reference time interval. Linear regression analysis was performed to identify, for each cultivar, the climate variables that enhanced the interplay between weather and maturation anomalies underlining the time intervals that influence most of the ripening dynamics. Linear regression was performed by forcing the intercept to zero (line passing through origin). This solution, indeed, enabled a simple and direct quantification of the weather anomaly effect onto a specific number of days in advance or delays compared to the mean trend for each ripening threshold. The most significant linear relationships of grape berry quality ripening parameters with climate variables were determined based on the coefficient of determination (R^2).

RESULTS

The results are presented in the following order: i) weather anomalies that occurred in the Northeast of Italy are presented by analysing the past 13 years of meteorological data measured at the weather station of Lonigo; ii) the changes to the different grape ripening dynamics measured at different times of maturation within the same period are described; iii) the relationships between the anomalies detected in the climate dataset and those obtained from the grape ripening evolution are presented and iv) the most significant relationships between ripening and weather anomalies are reported enabling an empirical modelling framework to support management decision for backward agronomic assessment and future impacts forecast.

1. Weather anomalies assessment

Figure 2 shows the distributions of weather anomalies detected within the 2009–2021 period in terms of precipitations totals (P_{sum}, Figure 2B), maximum (T_{max}, Figure 2C) and minimum temperatures (T_{min}, Figure 2D). For each time interval (month, bimester) are reported weather anomalies against the time period average (2009–2021).

On an annual scale, two vintages showed a positive rainfall anomaly of +413 mm (2014) and +295 mm (2010), positioning themselves at the 75° percentile of the distribution (Figure 2B). At the other end of the distribution, the year 2017 resulted in the driest year, placing at the 25° percentile, with –258 mm from the average. Looking at the monthly and bimester time intervals, several outliers (5°/95° percentiles, red circles in Figure 2) were detected both as positive and negative anomalies. Overall, the year 2014 exhibited a positive anomaly in the Jan–Feb and Jul–Aug bimesters. During the summer period, years 2020 (Jun–Jul, Jul–Aug) and 2010 (Sep, Sep–Oct) positioned above the 95° percentile. In autumn, the year 2019 was an outlier for November precipitation totals. For negative anomalies, dry period outliers were detected in Jul–Aug (2012) and Sep–Oct (2021). Overall, May was the month with the widest rainfall anomalies distribution, which ranged from more than 100 mm above and below the average.

Annually, 50 % of the distribution of T_{max} anomalies were between 0.1–0.3 °C above the average, with the years 2019 and 2011 being as much as +0.5 °C warmer than average (Figure 2C). Years 2010 and 2013 resulted in outliers with lower mean annual temperatures of about –1.3 °C and –0.7 °C against the time period average. Within the year, 2012 and 2017 had outliers in March, while 2015 had a July roughly +3–4 °C above average. More outliers were detected for T_{max} negative anomalies, mostly concentrated in the Feb–Mar bimester (2013, 2018) and in the second part of the summer (2014, 2017 and 2010). Interestingly, in 2014 the maximum temperatures of the bimester Jul–Aug were –3.3 °C below the average. This anomalous year significantly impacted grape ripening dynamics –described later.

On an annual basis, the year 2014 resulted as the only outlier for higher T_{min} anomalies of more than +1 °C above average, followed by the year 2018 in the 75° percentile with an annual T_{min} of +0.8 °C above average (Figure 2D). In terms of negative anomalies, the years 2017 and 2010 were the coldest, with mean minimum temperatures < –0.5 °C compared to average. For intra-annual variability, outliers were distributed evenly throughout the year, with only 2014 having a significant outlier in the winter quarter (Nov-Feb). During spring, the mean T_{min} during 2018 was 2 °C warmer than average. During the summer, the years 2015 and 2011 were +2.5 °C warmer than average T_{min} in July and September, respectively. Negative anomalies during the winter were seen in 2016, 2012 and 2017, with mean T_{min} cold extremes at –2.6 °C (Dec), –3.7 °C (Jan) and –4.4 °C (Feb), respectively. During the spring, 2021 showed the coldest Mar-May period and, during the summer, years 2021, 2010 and 2017 resulted in outliers in July and Sep–Oct intervals, respectively.

2. Grape ripening anomalies assessment

For each cultivar and berry ripening parameter, fitted non-linear function parameters on a calendar time basis, i.e., the set of parameters with the lowest residual sum of the squares, are summarised in Tables 1–3SM for TSS, TA and berry juice pH ripening parameters. The goodness of fit metrics for non-linear regression functions obtained for the four cultivars exhibited mean coefficients of determination for annual TSS, TA and pH datasets that ranged from 0.73–0.99, 0.78–0.98 and 0.75–0.99, respectively. Model agreement (RMSE, deviation between estimates and observations) ranged from 3.79 to 18.53 g/L TSS, 0.51–2.7 g/L TA and 0.03–0.14 pH, with model efficiency values higher than 0.75, 0.82 and 0.73 for TSS, TA and pH, respectively (Table 1–3SM). While the use of a thermal time basis would have improved the goodness of fit by greatly reducing overall RMSE ranges, the use of calendar time on a day of the year basis allowed this variability to be expressed. Indeed, such wide RMSE ranges can be explained by climate anomalies registered in the study area. Furthermore, by comparing two anomalies: climate and ripening, the use of thermal time for modelling ripening trends would have fall to autocorrelate with temperature anomalies.

The mean TSS, TA and pH seasonal dynamics for the period 2009–2021 on a calendar time basis are represented by solid red lines in Figures 1–3SM. Figure 3 shows the changes for GA (Figure 3A–C), GL (Figure 3D–F), CS (Figure 3G–I) and ME (Figure 3J–L) per day-of-year (DOY), grouped into 5-day intervals in graphs for TSS, TA and pH berry ripening parameters. The data represented in these graphs can be analysed in different ways. From the 5-day scale, indeed, it is possible to assess the development of grape maturity dynamics in terms of the day of the year (i.e., a variation on the X-axis). Moreover, for each vintage and cultivar, advances or delays in DOY to target specific sugar concentrations, total acidity and pH ripeness thresholds (Table 2) can be assessed with respect to the average ripening dynamics of the period 2009–2021. On the other hand, an analysis of the value of each variable on a specific day of the year (variation in the colour scale) reveals changes within each 5-day interval among different vintages and cultivars (Figure 3). At common maturity, as well as for overall ripening dynamics, there were significant differences in berry composition among vintages. TSS and TA levels and berry juice pH during maturation dynamics show common trends across cultivars for specific vintages with climate anomalies discussed in Section 1. Nonetheless, peculiar responses to environmental forcing variables enabled specific cultivar dependent behaviours related to inner cultivar characteristics of maturation earliness or lateness that are addressed below and summarised in Table 3. As pH is highly dependent on the total acidity values, and because the results obtained for pH are consistent with those obtained for TSS and total acidity, only mean berry juice pH anomalies trends are presented together with TSS and TA results hereafter. However, to allow a more comprehensive view of the analyses conducted and results obtained and to avoid obtaining redundant results, pH results are fully reported as Supplementary Material (Figures 4 and 5SM; Tables 4–6SM, Table 8SM).

Changes in TSS, TA and pH per day-of-year (DOY) are shown for cv. Gargangea in Figure 3A–C. Mean TSS increments for the average during 2009–2021 matched the first threshold of 50 g/L at approximately 20 of July and proceeded gradually to the target ripening threshold of 165 g/L at approximately 20 of September (Figure 3A). The same trend was observed for TA decreases and pH increments (Figures 3B,C). A wide variability across vintages is clearly visible, both considering given days in advance or delays, as compared to the average and anomalous ripening dynamics in given days to target the specified ripening thresholds. It is worth noting the 2014 vintage experienced a pronounced initial delay of about 10 days from average TSS and TA but by harvest,

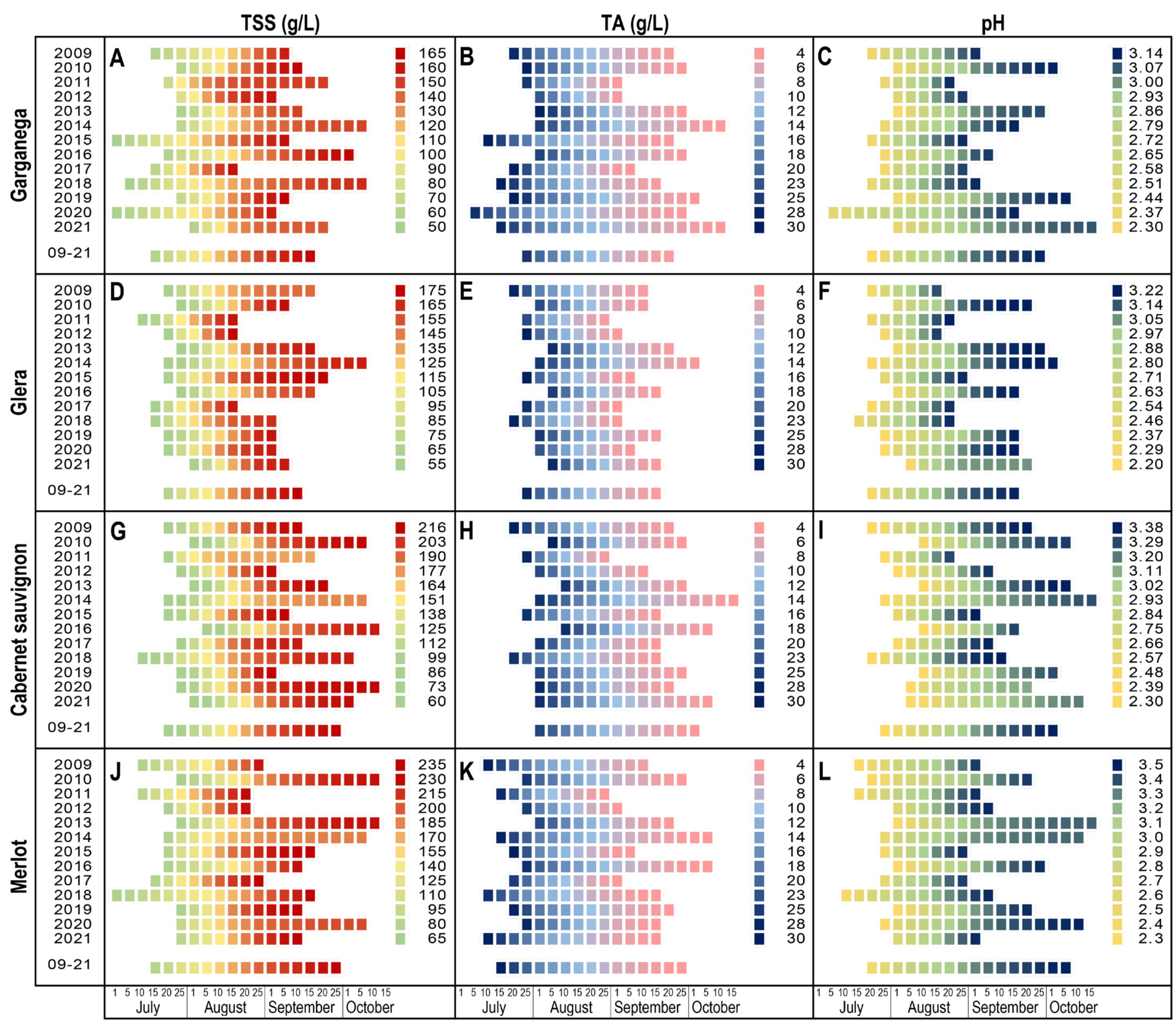

FIGURE 3. Dynamics of total soluble solids (TSS), total acidity (TA,) and pH per year and for the average period (2019–2021) in Garganega (A–C), Glera (D–F), Cabernet-Sauvignon (G–I) and Merlot (J–L). Each tile is calculated by applying the derived non-linear regression functions on a calendar basis using a 5-day sampling time frame (see Table 3 for a summary of main changes, best-fitting parameters and goodness-of-fit metrics are reported in Tables 1–3SM).

gained +21 days and +16 days to target the 145 TSS g/L and 5 TA g/L, respectively. A clear arrest of ripening is visible in the 2014 and 2021 vintages, especially for TSS ripening dynamics that did not reach the target threshold of 165 g/L leading to a clear decoupling with berry total acidity. Similar trends were observed in the 2016 and 2018 vintages that by harvest had gained delays of about +13 and +33 days to the target 150 TSS g/L threshold. The 2017 vintage, the driest year during 2009–2021 with about –300 mm of annual rainfall (Figure 3A–C), was characterised by an evident advance of ripening as compared to average, matching ripening thresholds of 160 g/L (TSS), 5 g/L (TA) and 3.14 (pH) by the 20–25 of August with –25, –16 and –23 days in advance, respectively. An interesting observation was seen during the 2011 and 2012 vintages when TA reached the target threshold of 5 g/L with –18 and –16 days in advance, respectively, as compared to average, but only the latter showed a similar arrest of the sugar maturation. This could be explained by the anomalous maximum temperature regimes experienced in both vintages during the summer (Aug–Sep) (Figure 2C).

The changes in TSS, TA and pH per day-of-year (DOY) are shown for cv. Glera in Figure 3D–F. Averages during 2009–2021 show a uniform ripening dynamic for TSS, TA and pH, revealing initial and ripeness thresholds at about the 20-25th of July and the 15th of September, respectively (Figure 3D–F). As observed for cv. Garganega, cv. Glera exhibited a clear ripening delay in the 2014 vintage in terms of TSS, TA and pH dynamics due to the lowest maximum temperature regimes experienced during the summer period (Figure 2C). This led to an average delay of about +20 and +15 days to the specified target TSS (175 g/L) and TA-pH (5 g/L and pH 3.22) thresholds at maturity, respectively. Anomalous warm summer temperatures during the 2011 and 2012 vintages caused an acceleration of sugar accumulation of about –23 and –26 days in advance to the target 175 g/L TSS threshold and a rapid acidity breakdown (Figure 3E,F) with mean delays of about –24 days (TA) and –20 days (pH) as compared to average. A clear sugar-acidity decoupling is visible during the 2021 vintage with TSS values at harvest that matched the average, while TA and pH showed a maturation arrest particularly visible for berry pH that arrested at values of 3.00 without reaching the last ripening threshold of pH 3.16.

For this location, the average 2009–2021 ripening dynamics for TSS, TA levels and berry juice pH show that ripeness thresholds are reached in cv. Cabernet-Sauvignon at about the end of September on average (Figure 3G–I). A significant delay also occurred in CS during vintages 2014, 2016 and 2020. Unlike the 2014 vintage, where the delay in maturation materialised in the second part of the season with the initial TSS 95 g/L threshold that matched the average, a significant delay occurred from the beginning of the ripening period in 2016 and 2020 of about +10 and +15 days, respectively, resulting in at about +18 days of delay at maturity (215 g/L TSS) (Figure 3G). Nevertheless, unlike the years 2016 and 2020, the vintage 2014 shows a visible maturation arrest that prevented berry sugar increments from targeting the 180 g/L thresholds. Similar to 2014, the 2021 vintage exhibited dynamics for berry juice pH levels that did not meet ripening thresholds with mean delays of about +20 days (Figure 3I). The warm vintages of 2012, 2015 and 2019 each showed a similar structure in berry sugar ripening that occurred in the last ten days of August, yielding final advances of more than +15 days to target specified ripening thresholds.

Similar trends were observed for cv. Merlot (Figure 3J–L) as described for Cabernet-Sauvignon. Mean ripening of the grapes of this cultivar commonly occurs in

TABLE 3. Summary of the main changes (advances or delays) of TSS, TA and pH per year against the average time period (2009–2021) in the four studied cultivars.

Ripening variable	TSS				TA				pH			
Vintages / Cultivar	GA	GL	CS	ME	GA	GL	CS	ME	GA	GL	CS	ME
2009	↓	=	↓↓	↓↓	=	=	↓	↓↓	↓↓↓	↓↓↓	↓	↓↓↓
2010	↓	↓	↑↑↑	↑↑↑	=	=	=	=	=	=	↑	↓
2011	=	↓↓↓	↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓
2012	↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓	↓↓↓
2013	=	=	=	↑↑↑	=	=	=	=	=	↑	=	↑↑↑
2014	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↓	↑↑↑	↑↑↑	↑↑↑
2015	↓	↑↑	↓↓↓	=	=	↓	↓↓	↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓
2016	↑	=	↑↑↑	↓	=	=	=	↑↑↑	↓↓	=	=	=
2017	↓↓↓	↓↓↓	↓↓	↓↓↓	↓↓↓	↓↓	↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↓↓
2018	↑↑↑	↓	=	↓	↑	↓↓	↓↓	=	↓↓↓	↓↓↓	↓↓↓	↓↓
2019	↓	↓	↓↓↓	=	=	=	=	=	↑↑	=	=	↓
2020	↓↓	↓	↑↑↑	↑↑↑	=	↓	↓	=	=	=	↓	↑↑↑
2021	↑	=	=	↓	↑↑↑	=	=	=	↑↑↑	↑	↑↑	↓↓

*↓ advance of ripening; ↑ delay of ripening; = on average as compared to 2009–2021 time period; arrest of ripening is formatted in red colour. CS Cabernet-Sauvignon, ME Merlot, GA Garganega, GL Glera, TSS total soluble solids, TA total acidity.

the Northern Hemisphere in the period between the last ten days of September and the first ten days of October. Common characteristics retrieved from modelled ripening functions for the average time period 2009–2021 ripening dynamic for TSS, TA levels and berry juice pH fell within the common window of ripening dynamics observed for the cultivar (Figure 3J–L). Unlike cv. Garganega and Glera, due to their common mid-late maturation period, for Merlot and Cabernet-Sauvignon, the weather conditions in the last part of the summer (Sep–Oct) significantly impacted the ripening dynamics. Significantly delayed maturation was observed in 2010, 2013, 2014 and 2020 vintages, with average delays of about +15, +13, +10 and +7 days to target maximum thresholds of berry TSS at maturity. Nevertheless, while in the first two vintages, the grapes were able to complete the maturation (225–235 g/L), this was not observed in 2014 and 2020, with an evident arrest of maturation at TSS thresholds of about 180 and 200 g/L, respectively (Figure 3J). TA levels and juice pH characteristics followed the same common dynamics of TSS underlying the cessation of pH increments and TA decrements in the last part of the ripening period (Figure 3K–L). Significant advances were observed for the vintages of 2011, 2012 and 2017, which yielded maximum ripeness thresholds at about 25–27 days before average.

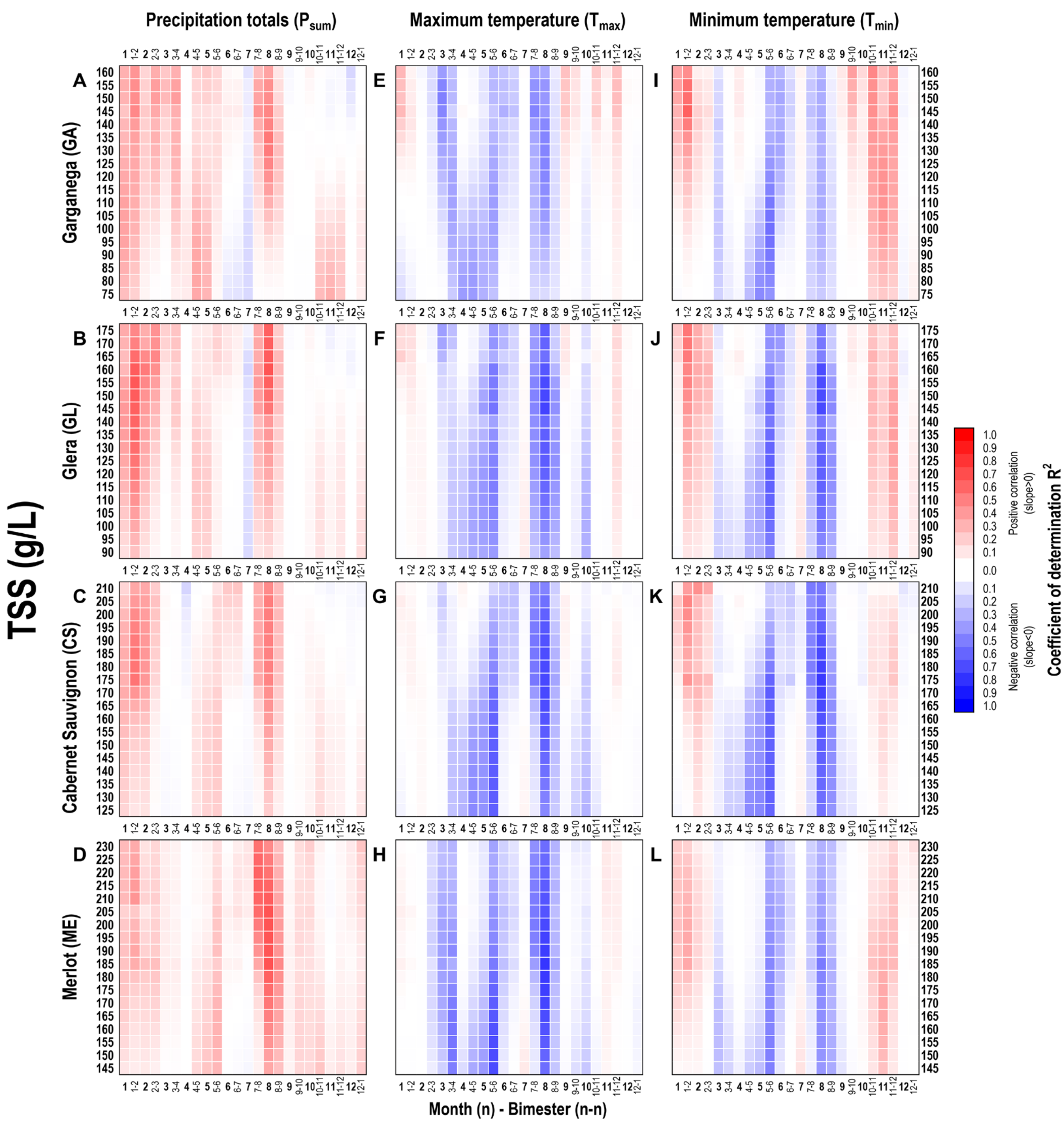

FIGURE 4. Heatmaps showing R^2 values of linear regression analyses performed between anomalies of climate indicators: P_{sum} (A–D), T_{max} (E–H), T_{min} (I–L) and ripening anomalies, expressed as advances or delays in days to 18 target ripening thresholds for Total Soluble Solids (TSS) in Garganega (A,E,I), Glera (B,F,J), Cabernet-Sauvignon (C,G,K) and Merlot (D,H,L) during the ripening at different time intervals, reported as month (*n*) or bimester (*n-n*). Colour-scale gradient shows where a positive (red) or negative (blue) slope coefficient was obtained through standard linear regression analysis performed by forcing the intercept to zero (line passing through origin). Slope coefficients (± SE) for most significant relationships (R^2 > 0.5) are reported as Supplementary Material Tables 4–9SM.

3. Relationships between grape ripening and weather anomalies

Exploratory linear correlation analysis between the observed anomalies of climate variables at different time intervals during the growing season and berry component dynamics throughout the ripening period enables the identification of the climate variables and the most critical periods that were influential on berry composition. Furthermore, for each cultivar, a quantification of the impact of climate variables in terms of ripeness advances or delays expressed in the number of days to the specific target ripening thresholds was assessed. Multi-panel Figures 4 and 5 show the results of the linear regressions, expressed as coefficient of determination (R^2), between the specified anomalies for each climate variable (P_{sum}, T_{max}, T_{min}) within specific time intervals (month, bimester) and the ripening anomalies (number of days in advance or delay to target ripening thresholds). Results for simple linear regression analysis were performed by forcing the intercept to zero (line passing through origin). For a better understanding of the linear regression procedure, in Figure 6 are reported some examples of the best relationships obtained between climate anomalies and ripening anomalies to target the specified ripening thresholds as compared to the average time period (2009–2021).

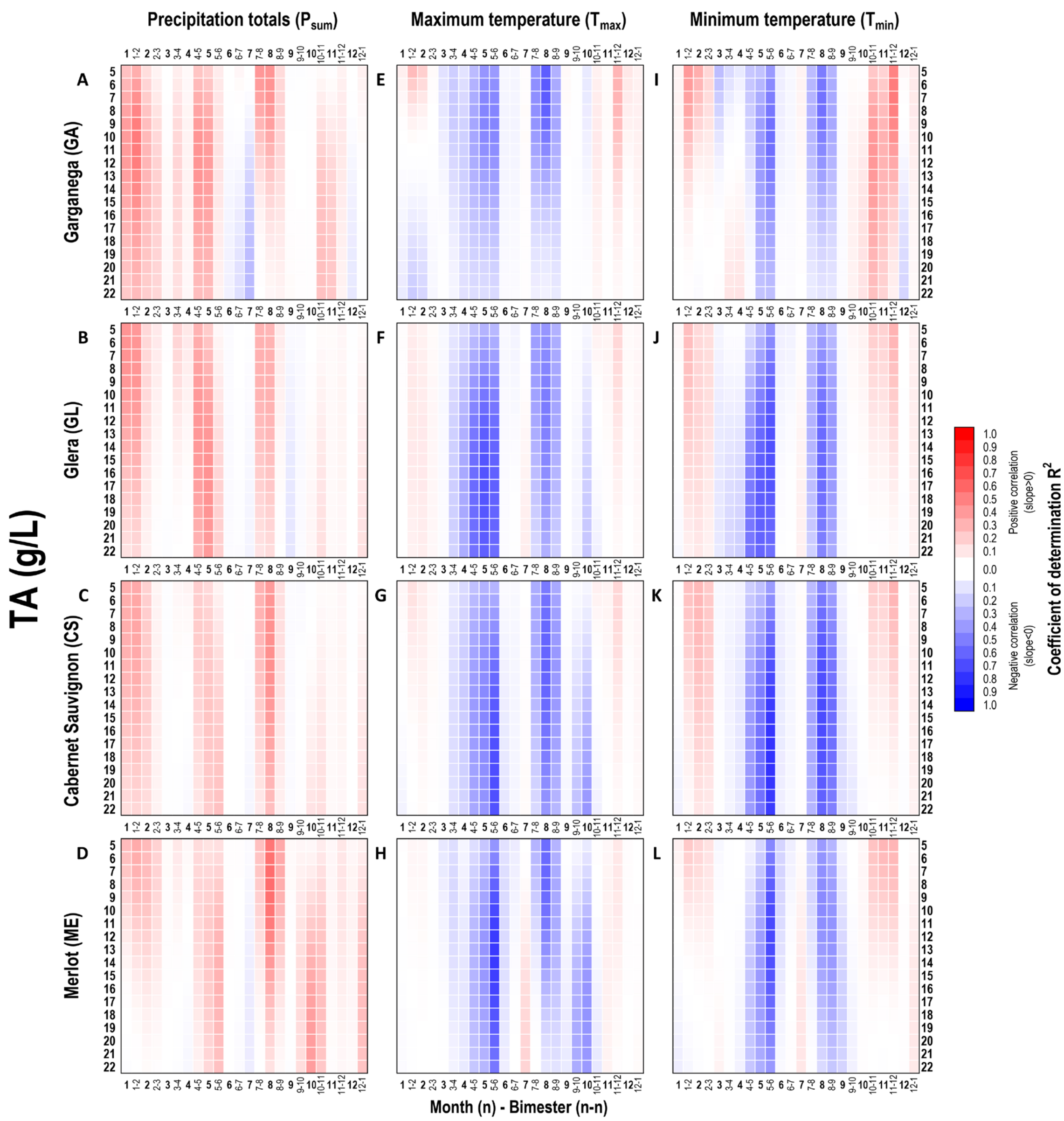

FIGURE 5. Heatmaps showing R^2 values of linear regression analyses performed between anomalies of climate indicators: Psum (A–D), Tmax (E–H), Tmin (I–L) and ripening anomalies, expressed as advances or delays in days to 18 target ripening thresholds for Total acidity (TA) in Garganega (A, E, I), Glera (B, F, J), Cabernet-Sauvignon (C, G, K) and Merlot (D,H,L) during the ripening at different time intervals, reported as month (*n*) or bimester (*n-n*). Colour-scale gradient shows where a positive (red) or negative (blue) slope coefficient was obtained through standard linear regression analysis performed by forcing the intercept to zero (line passing through origin). Slope coefficients (± SE) for most significant relationships (R^2 > 0.5) are reported as Supplementary Material Tables 4–9SM.

3.1. Total soluble solids (TSS)

Total soluble solid anomalies correlate with climate indicators most significantly in summer during the warmest month of the year (August), more marginally but consistently across four cultivars during late spring (May–June bimester) and marginally in GL and CS during the Jan–Feb bimester (Figure 4). Precipitation of the warmest month (August) positively correlated with TSS development and provided the key to understanding the effect of climate change on sugar ripeness, particularly in the last ripening stages (Figure 4A–D). The effects of precipitation anomalies during August on TSS dynamics positively correlated with berry sugar increments. Consistently across cultivars, temperatures facilitated the understanding of the climate effect on advances or delays in sugar ripeness by negatively correlating most significantly during late spring (May–June bimester) and during the warmest month (August), following a gradual shift from early ripening thresholds towards later ones, respectively (Figure 4). While less significant than other variables described above, precipitation totals and minimum temperatures during the January to February bimester positively correlated with the latest TSS thresholds at maturity.

3.2. Total acidity

Total acidity anomalies correlate with climate indicators most significantly in late spring (May-June bimester) with initial ripening thresholds and in summer during the warmest month of the year (August) (Figure 5). Precipitation totals during the warmest month positively correlate with TA breakdown during the last ripening stages (TA < 10 g/L), particularly in Garganega, Cabernet-Sauvignon and Merlot. Total acidity anomalies during the initial ripening thresholds positively correlated with late spring bimester rainfall anomalies (May–June) in white cultivars (GA, GL) (Figure 5A–D). These results provide additional information that is key to understanding the effect of climate change on berry acidity decrements. Consistently across all four cultivars in this study, temperatures are significant to understanding the climate effect on advances or delays in total acidity evolution by negatively correlating most significantly during late spring (May–June bimester) and during the warmest month (August). As was observed for TSS relationships, a clear shift from early ripening thresholds, impacted by anomalous spring temperature regimes, towards later stages was mostly affected by August (GA, GL) and August–September bimester in red cultivars (CS, ME) (Figure 5E–L). Moreover, similar to TSS, precipitation totals and minimum temperatures of the January to February bimester exhibited lower significance than other variables but positively correlated with the latest TA thresholds.

4. Best relationships between climate and ripening anomalies assessment

Figure 6 reports some of the best relationships (R^2 higher than 0.5) in terms of TSS and TA berry composition anomalies with climate variables anomalies. In terms of berry TSS anomalies, the highest positive correlation was observed with the climate anomaly indicator 'Precipitation totals' (P_{sum}) during the warmest month for Merlot to target 200 g/L TSS (Figure 6A, R^2 = 0.73). The higher the precipitation total during this interval period (variation on the X-axis), the higher the delay in the number of days to specified target ripening thresholds (variation on the Y-axis). A delay of about +3 days (slope m = 0.3) occurred for every 10 mm more precipitation during the warmest month compared to average. Overall, observing the different data reported in Figure 6, the anomalous behaviour of the wet vintages in 2014 and 2016 is clearly visible: an anomaly of about +50 mm in August resulted in more than 20 days of delay to target TSS 200 g/L. The same concept can be applied to dry vintages, as seen in 2012 and 2011, with an advance of about –20 days with precipitation anomalies of –50 and –60 mm observed in August, respectively.

The highest negative correlations for TSS were observed with maximum (T_{max}) and minimum temperatures (T_{min}) during the warmest month in Glera, Merlot and Cabernet-Sauvignon to target TSS thresholds of 175 (R^2 = 0.64), 185 (R^2 = 0.77) and 175 g/L (R^2 = 0.77), respectively (Figure 6B–D). For example, considering the negative relationship between the anomaly of the T_{max} climate indicator during the warmest month and the number of days to target the 185 g/L TSS in Merlot presented in Figure 8C, an advance of about 6 days (slope m = –5.85) occurred for every given 1 °C from average T_{max} during the warmest month.

The best relationships in terms of TA grape ripening anomalies and climate variables are reported in Figure 6E–H. It is worth noting for wet vintages such as 2014, 2016 and 2010, as well as for the dry vintages such as 2017, 2009 and 2011, a consistent positioning at the opposite chart quadrants along the linear trendline.

The highest negative relationships between TA and climate anomalies were observed for T_{min} for Cabernet-Sauvignon with advances or delays to the target 18 g/L threshold (R^2 = 0.80, Figure 6E). Other highly significant relationships are seen for T_{max} during spring (May) for Glera and Merlot and during the warmest month for Cabernet-Sauvignon to initial target ripening TA thresholds of 13 g/L (R^2 = 0.77) and the latest threshold of 5 g/L at Garganega maturity (R^2 = 0.63), respectively (Figure 6F–H). Warmer mean temperatures (T_{max} and T_{min}) during late spring and during the warmest month (a variation on the X-axis), the greater the advances in the number of days to specified target total acidity ripening thresholds (a variation on the Y-axis). The relationship between the anomalies of T_{max} of the warmest month and the total acidity levels in Garganega at maturity can be used as an example (Figure 6H), where an advance of about 6.5 days (slope m = –6.47) occurred for every 1 °C warmer T_{max} during August compared to average.

4.1. Development of decision support algorithms for backward agronomic assessment and future impact forecasts

While previous sections enable a clear analysis of the most significant and, therefore, critical time intervals for berry

TSS and TA maturation dynamics (see Figures 4–5), further quantification of these impacts was also evaluated from the most significant relationships (see Figure 6). By analysing the slopes of the climate and ripening anomalies relationships, predictive algorithms may be developed to better characterise future vintages by forecasting a grape maturity profile or a potential advance/delay in the ripening. In Table 4, the slopes of the most significant linear regression functions for cv. Cabernet-Sauvignon between climate indicators and ripening (TSS, TA) anomalies for the 18 thresholds selected during the ripening period considering a minimum R^2 of 0.5 are reported. For each cultivar, the advance or delay in days to reach each target ripening threshold can be easily estimated by multiplying a given climate anomaly unit (mm or °C) per the slope coefficient of the relationship (as the intercept was forced to zero). Slope coefficients (± SE) for most significant

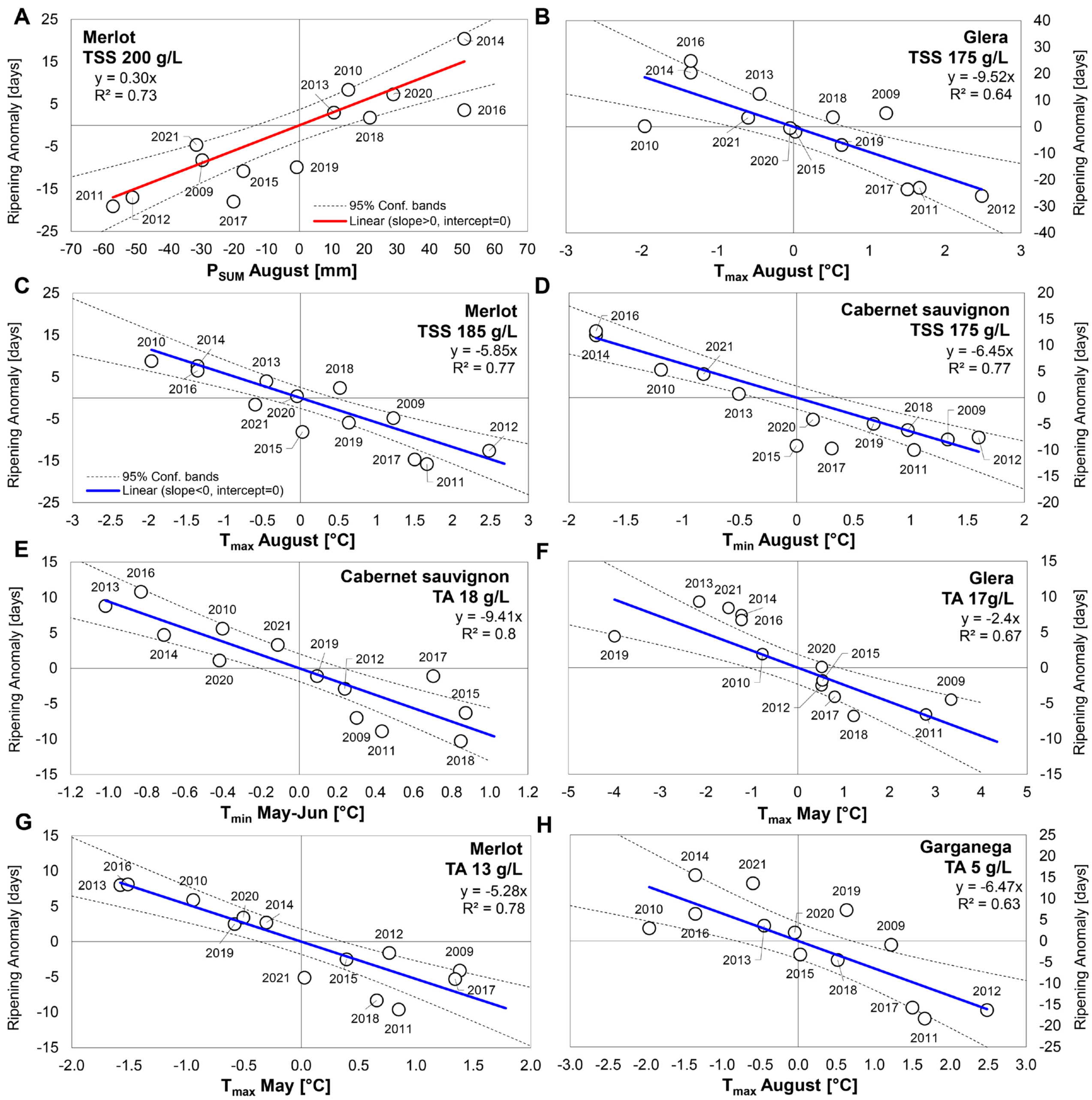

FIGURE 6. Some of the most significant relationships obtained by standard linear regression analysis between anomalies of climate indicators (P_{sum}, T_{max}, T_{min}) during given time intervals and ripening anomalies expressed as days in advance or delay to specific target TSS (A–D) and TA (E–F) thresholds during the ripening period. Solid lines represent the linear regressions with positive (red) or negative (blue) slope coefficients. Dashed lines represent 95 % confidence bands. For each cultivar, advance or delay in days to target each ripening threshold can be easily estimated by multiplying a given climate anomaly unit (mm or °C) per the slope coefficient of the relationship. Slope coefficients (± SE) for most significant relationships (R^2 > 0.5) are reported as Supplementary Material Tables 4–9SM.

TABLE 4. The slope of linear regression functions for the cv. Cabernet-Sauvignon cultivar between climate indicators and ripening (TSS, TA) anomalies for the 18 thresholds selected during the ripening period (see Table 2).

Ripening variable		TSS (g/L)									TA (g/L)					
Climate indicator		P_{SUM}		T_{max}			T_{min}				T_{max}		T_{min}			
month (n) - bimester (n-n)	g/L	1–2	8	5–6	7–8	8	5–6	7–8	8	g/L	5–6	8	5	5–6	8	8–9
	210							−10.85 ± 3.03	−8.17 ± 2.19	5		−7.02 ± 1.96				
	205		0.24 ± 0.07			−6.67 ± 1.71			−7.69 ± 2.06	6		−6.46 ± 1.7			−7.48 ± 2.04	
	200		0.21 ± 0.06			*−6.31 ± 1.43*			−7.28 ± 1.74	7		−6.01 ± 1.52			−7.08 ± 1.79	
	195				−5.68 ± 1.6	*−6.02 ± 1.27*			*−7.02 ± 1.52*	8		−5.64 ± 1.37		−11.41 ± 2.99	*−6.73 ± 1.58*	
	190	0.17 ± 0.05			−5.42 ± 1.49	*−5.78 ± 1.15*			*−6.8 ± 1.35*	9		*−5.31 ± 1.26*		*−11.12 ± 2.63*	*−6.44 ± 1.41*	
	185	0.16 ± 0.04			−5.2 ± 1.41	***−5.6 ± 1.07***			***−6.68 ± 1.22***	10	−6.24 ± 1.74	*−5.02 ± 1.18*		*−10.85 ± 2.34*	*−6.18 ± 1.29*	−6.45 ± 1.82
	180	0.16 ± 0.04			−5.01 ± 1.35	***−5.43 ± 1.01***	−8.8 ± 2.78	−7.28 ± 2.09	***−6.56 ± 1.11***	11	−6.13 ± 1.58	*−4.77 ± 1.11*		*−10.59 ± 2.09*	*−5.95 ± 1.18*	−6.23 ± 1.69
	175	0.15 ± 0.04			−4.81 ± 1.32	***−5.27 ± 0.96***	*−9.64 ± 2.39*	−7.03 ± 2.02	***−6.45 ± 1.01***	12	−6.04 ± 1.47	*−4.56 ± 1.08*		***−10.4 ± 1.91***	*−5.76 ± 1.12*	−6.04 ± 1.6
CABERNET SAUV. Ripening threshold	170			*−5.74 ± 1.47*		***−4.85 ± 0.88***	*−9.51 ± 2.11*		***−5.84 ± 0.98***	13	*−5.96 ± 1.35*	−4.36 ± 1.04	−4.52 ± 1.3	***−10.2 ± 1.73***	***−5.58 ± 1.05***	−5.88 ± 1.51
	165			−5.83 ± 1.41		***−4.75 ± 0.9***	*−9.35 ± 2.12*		***−5.64 ± 1.04***	14	*−5.88 ± 1.26*	−4.16 ± 1.02	−4.45 ± 1.23	***−10 ± 1.6***	***−5.41 ± 1.01***	−5.73 ± 1.45
	160			*−5.86 ± 1.37*		*−4.6 ± 0.93*	*−9.21 ± 2.11*		*−5.44 ± 1.09*	15	*−5.8 ± 1.2*	−4 ± 1.02	−4.4 ± 1.18	***−9.85 ± 1.51***	***−5.26 ± 0.99***	−5.59 ± 1.41
	155			*−5.81 ± 1.32*		*−4.42 ± 0.95*	*−9.02 ± 2.08*		*−5.25 ± 1.1*	16	*−5.73 ± 1.15*	−3.84 ± 1.01	−4.33 ± 1.15	***−9.69 ± 1.44***	*−5.11 ± 0.98*	−5.44 ± 1.38
	150			*−5.77 ± 1.29*		*−4.26 ± 0.98*	*−8.91 ± 2.05*		*−5.1 ± 1.12*	17	*−5.66 ± 1.11*	−3.7 ± 1.02	−4.28 ± 1.11	***−9.54 ± 1.39***	*−4.98 ± 0.97*	−5.32 ± 1.36
	145			*−5.73 ± 1.26*		−4.1 ± 1	*−8.8 ± 2.01*		*−4.97 ± 1.13*	18	*−5.6 ± 1.09*		−4.23 ± 1.1	***−9.41 ± 1.37***	*−4.86 ± 0.98*	−5.2 ± 1.36
	140			*−5.68 ± 1.24*		−3.96 ± 1.02	*−8.72 ± 1.99*		*−4.86 ± 1.14*	19	*−5.57 ± 1.07*		−4.2 ± 1.09	***−9.33 ± 1.37***	*−4.77 ± 1*	−5.11 ± 1.36
	135			*−5.64 ± 1.23*		−3.83 ± 1.05	*−8.66 ± 1.98*		*−4.76 ± 1.15*	20	*−5.51 ± 1.07*		−4.15 ± 1.08	***−9.2 ± 1.38***	*−4.65 ± 1.02*	−5 ± 1.37
	130			*−5.57 ± 1.24*			*−8.57 ± 1.98*		*−4.65 ± 1.17*	21	*−5.46 ± 1.07*		−4.12 ± 1.08	***−9.09 ± 1.41***	*−4.56 ± 1.04*	−4.92 ± 1.38
	125			*−5.53 ± 1.24*			*−8.49 ± 1.99*		*−4.57 ± 1.19*	22	*−5.41 ± 1.08*		−4.08 ± 1.08	***−8.97 ± 1.44***	*−4.45 ± 1.06*	

Slope values (± SE) of the most consistent linear regression relationships (intercept = 0), deemed significant with $R^2 > 0.5$, between climate indicators (T_{max}, T_{min}, P_{sum}) for specific time intervals (year, month or bimester) and ripening anomalies for each ripening threshold. Values are formatted according to the consistency of the relationship: $0.5 \leq R^2 < 0.6$ (normal); $0.6 \leq R^2 < 0.7$ (*italic*); $0.7 \leq R^2 < 0.8$ (***bold-italic***) and $R^2 \geq 0.8$ (***red bold-italic***). The empty cells mean that the relationship was not deemed significant ($R^2 < 0.5$). TSS = Totals Soluble Solids (g/L); TA = total acidity (g/L); T_{max} = maximum temperature; T_{min} = minimum temperature, P_{sum} = precipitation totals.

relationships ($R^2 > 0.5$) for remaining cultivars are reported as Supplementary material Tables 4–9SM.

Within almost all given climate indicators and time intervals (single column variation), an increasing trend of the slope coefficients in absolute value is observed as ripening thresholds proceed with maturation. The higher (for TSS) or lower (for TA) the levels of maturation proceeding towards the harvest date, the higher (more positive for positive relationships, slope > 0; more negative for negative relationships, slope < 0) the slope coefficient (Table 4). For example, considering the impact of anomalous maximum temperatures, within the warmest month (August), for Cabernet-Sauvignon berry total acidity levels ranging from 17 to 5 g/L, a gradual increase of the slope values (more negative) occurs from about –3 to –7. As a result, for every 1 °C warmer August T_{max} anomaly from average (2009–2021), a greater impact expressed as the number of days in advance to the target ripening threshold is obtained, from just an advance of 3 days (to target 17 g/L of total acidity) up to 7 days for TA levels at maturity. This approach can be easily transferred to every other series of relationships within a given climate anomaly time interval. The wider the ranges of the slope values, the greater the impact on ripening advance or delay increments by progressively proceeding towards harvest.

DISCUSSION

The aim of this research was to investigate the influences of climate variables on berry TSS, TA and juice pH for four major winegrape cultivars and to analyse possible anomalous relationships between ripening and climate against the average time period (2009–2021) to develop an empirical modelling framework that describes the observed responses and provides forecasting purposes. Weekly berry sampling at twelve study vineyards located in northeast Italy provided the relevant berry composition dataset. While a 13-year period may not be long enough to capture the entire structure of the climate trends, the results obtained in the present study are consistent and in agreement with studies conducted on shorter and longer time periods (Barnuud *et al.*, 2014; Bécart *et al.*, 2022; Costa *et al.*, 2020; Meggio *et al.*, 2022; Parker *et al.*, 2011). A comparative analysis was performed to evaluate whether the use of a longer climate time series of 30 years, available from the same weather station, would have impacted the results of the study. The obtained results, reported as Supplementary material in Table 10SM, were obtained by comparing the coefficients of determination of a selection of the best relationships (R^2 higher than 0.5) between climate anomalies and ripening anomalies of TSS and TA (as the number of days in advance or delay to target the specific ripening thresholds) considering two different time periods: 2009–2021 (13 years) and 1992–2021 (30 years). As can be observed in Table 10SM, the results are significant and the relationships are consistent across the four cultivars, confirming the time intervals that affect most of the ripening dynamics. In some cases, the coefficient of determination was even slightly improved by considering the 30-years baseline. While the 13-year period selected in the present study to match the ripening dataset does not allow one to properly refer to the anomalies against a climate baseline, the results suggest that even considering a shorter time scale, the modelling framework developed in this study is consistent in four contrasting cultivars and can be obtained to track the impact of climate anomalies on ripening dynamics.

While regression analyses between anomalous maturity thresholds and climate indicators confirm known relationships, such as TA or TSS and temperature or precipitation regimes, some interesting findings are presented hereafter. It is worth noting that the results were consistent across cultivars, climate variables and even observed ripening parameters, with no ripening anomaly being best correlated with early summer (June, July and June–July bimester). Unfortunately, no phenological data are available for the present study preventing the possibility of the results reported in a recent comprehensive study by Bécart *et al.* (2022), where no significant correlations were found on a half-century ripening dataset in Grenache between ripening parameters at harvest, and more than 15 climate indicators in the Flowering-to-Fruit Set phenological phase neither for total acidity, potential alcohol and 200-berry weight.

1. Weather anomalies influence on rates of change of TA (and pH)

Assessments of total acidity (TA) and berry juice pH are used to help define the optimum time for harvest for a particular wine style. Both are known to significantly impact wine typicity and quality. In the present study, for all four cultivars, regression analysis between climate variables anomalies during the time period (2009–2021) and ripening anomalies in terms of number of days in advance or delay to specified target ripening thresholds, have discerned several salient features: i) TA anomalies are negatively correlated with all-temperature indicators (T_{max} and T_{min}), ii) climate-to-ripening anomaly relationships yield the most significant relationships during the late-spring May-to-June bimester and during the warmest month (August); iii) by contrast, the TA anomaly relationships with rainfall are almost always positive and iv) the strength of the significance (higher coefficient of determination), regardless of the sign, between TA anomalies and climate indicators increases steadily from early ripening thresholds, at early season stages, towards late-ripening thresholds indicating that the weather anomalies at maturity are the most influential on determining berry advances or delays at maturity.

In agreement with previous studies and consistently across the four cultivars, it is worth noting that some of the strongest and most significant negative relationships of TA were with maximum temperatures that occurred during the warmest month (Barnuud *et al.*, 2014; Bécart *et al.*, 2022; Costa *et al.*, 2020). Indeed, organic acid degradation starts at véraison, which is mainly driven by temperature with positive effects on the berry juice pH. Acid metabolism has been widely studied and the dependence of the quantity of malic acid on environmental conditions is well-known (Buttrose *et al.*, 1971; Lakso and Kliewer, 1975, Lakso and Kliewer, 1978;

Ruffner *et al.*, 1976). Considering that in the berries, tartaric and malic acids constitute most (up to 92 %) of the total acidity (Kliewer, 1973) but, unlike the amount of tartaric acid, malic acid is much more stable and its metabolism much slower; therefore the degradation of the berry acids through respiration, particularly malic acid, increases with increasing temperatures (Coombe, 1987). High temperatures during both the daytime and night-time, or during conditions of water stress, are the main factors capable of noticeably reducing grape acid contents, especially malic acid, which is degraded with a greater intensity compared to its biosynthesis. From this point of view, the acid-to-sugar ratio at harvest is important to building grape flavour, which is fundamental for the taste of grapes and ultimately determines wine quality and typicity (Conde *et al.*, 2007; Kuhn *et al.*, 2014). Within a changing climate, it is important to limit the anticipated ripening thresholds being met during the hottest part of the summer leading to thermal decoupling of berry traits which likely contributes to unbalanced wines: too high alcohol levels, lacking in acidity, freshness and poor aromatic bouquet (Duchêne *et al.*, 2010; Parker *et al.*, 2020; Petrie and Sadras, 2008; Sadras and Moran, 2012; van Leeuwen and Seguin, 2006). The modelling framework proposed in the present study enabled the arrest of grape maturation to be assessed both qualitatively and quantitatively by underling the climate variables and most critical time intervals during the season that significantly impact sugar-to-acid decoupling under heat stress and excess or deficits in rainfall. Significant relationships between TA anomalies and minimum temperatures yielded consistent significant results across cultivars, with the strength of the correlations increasing steadily as the season progressed, becoming strongest during the ripening period. Overall, these results are in agreement with those reported in the literature. Barnuud *et al.* (2014) report in a study conducted on Cabernet-Sauvignon, Chardonnay and Shiraz in Western Australia that TA levels at maturity are negatively correlated to temperature (and temperature-derived variables), with the most significant relationships observed with maximum temperatures during the ripening period. A study conducted in the Portuguese wine regions of Douro, Dão and Alentejo by Costa *et al.* (2020) reports that a consistent early drop in TA (and increase in pH) was negatively correlated with all monthly temperature regimes from June to August. A recent study conducted on Grenache by Bécart *et al.* (2022) on a 50-year ripening dataset in the Rhone Valley reported that low acidity levels at harvest were linked to strong early-season water deficits in the Budburst-Flowering phase, possibly explained by limited grapevine nitrogen and potassium absorption, with nitrogen affected directly due to limited water availability in the soil during the spring, and potassium indirectly promoted by lower canopy growth.

As reported above, only the variations in precipitation summations were found to have positive influences on TA levels during berry ripening by delaying the day to target a given TA level. Rainfall anomalies, either early (May–June) or later (August) in the season or even considering the entire growing season, had a positive impact on TA levels anomaly showing a significant delay in the number of days to target a given TA threshold. These results are in agreement with those reported by Barnuud *et al.* (2014) and (Costa *et al.*, 2020). This result can be explained by an indirect influence of anomalous rainfall regimes on lowering TA decreases at maturity via lowering of air temperature regimes as rainfall increases and by incrementally affecting vegetative growth due to increased water availability, both of which would sustain TA levels and delay ripening. In the present study, an average delay of about 2 days to target TA levels of 10 g/L in Merlot and Cabernet-Sauvignon were influenced by a positive anomaly during the warmest month (August), or over the entire year, of about 10 mm and 100 mm from average, respectively. Given the role that water availability plays in determining grapevine productivity and fruit composition at maturity, wine regions that are already experiencing reduced precipitation regimes or, more importantly, in those for which reduced precipitation is a predicted component of climate change, will need to undergo significant adaptation strategies over the coming decades (Santos *et al.*, 2020). Recent studies reported how carbohydrate availability and their allocation patterns play a key role in the adaptation of berry development to environmental changes (Rienth *et al.*, 2016). From this point of view, the adoption of sustainable vineyard management solutions to improve the water use efficiency and adaptation capacity of actual viticultural systems to future scenarios is becoming mandatory to maintain the economic viability of the entire wine chain (Ashenfelter and Storchmann, 2014; van Leeuwen and Destrac-Irvine, 2017).

2. Weather anomalies influence on ripening rates of change in TSS

After véraison, the grape berry is subject to a series of coordinated chemical and metabolic changes of considerable magnitude (Kuhn *et al.*, 2014). The phenomenon of maturation is a very fascinating aspect of physiology, but there is still much to understand about the effects of climatic variables and their interactions on the multiple, complex, and often non-linear transformations that affect the berry. While the present analysis of the relationships between anomalous maturity data and climate variables confirms known relationships, it also highlights some noteworthy results. Late spring May-to-June bimester anomalies in maximum temperatures were most significant for Cabernet-Sauvignon and Merlot, being negatively linked to the earliest ripening thresholds. This period is associated with the Flowering phase for all cultivars studied. Anomalous maximum temperatures in this phenological phase have a strong negative impact on berry ripening leading to a mean advance of about 6 days to target TSS ripening thresholds (i.e., 160 g/L TSS) for each 1 °C above the mean T_{max} of the time period (see Table 4 and Table 8SM). By comparing the slope values of the obtained relationships at the same TSS value, we can conclude that CS and ME have a similar significant sensibility to T_{max} at the Flowering phase. The same concept can be applied to T_{min} within the same time interval by comparing the four cultivars. For example, since at a given date, significant differences in berry TSS levels occur among red (CS, ME) and white (GA, GL) cultivars, TSS anomalies at the thresholds of 170 g/L and 105 g/L, respectively, were each found to negatively relate to T_{min} of May–June bimester anomalies ($R^2 > 0.5$) (Figures 3; Table 4, Tables 4–9SM). Anomalous T_{min} during Flowering was found to have a negative impact on berry ripening leading to a mean advance of about 8–9 days (CS, ME) and 7–8 days (GA, GL) to respective target TSS ripening thresholds every 1 °C above the mean T_{max} of the time period.

The factors which determine the physiology of sugar accumulation in the berry include all the processes which lead to maturation. Among these, photosynthesis is particularly important in relation to the total yield and to the partitioning of assimilates among source and sink organs.

While the positive effect of temperature on sugar accumulation has been clearly demonstrated, cardinal temperature limits required are almost always satisfied by optimal site condition selection; these, however, must be evaluated both in terms of crop load per vine and in relation to the amount of water available. If water availability is lower than plant requirements, high temperatures have a negative effect on sugar accumulation leading to progressive heating of the canopy, which in turn impacts the numerous physiological processes of berry maturation (Chaves *et al.*, 2010; Salazar Parra *et al.*, 2010; Zarrouk *et al.*, 2015). On the other hand, excess water availability can also play a negative role with effects on dilution of berry composition, ultimately delaying maturation (Ruperti *et al.*, 2019).

Increases in sugar accumulation have been observed and related to increased growing season temperatures (Parker *et al.*, 2020). In this study, regression analyses between anomalies of climate indicators and advances or delays in berry ripening dynamics indicated the following salient results: i) TSS anomalies are negatively correlated with all temperature indicators (T_{max} and T_{min}) during the growing season period, and consistently with T_{min}, which is positively linked to autumn and winter months; ii) by contrast, rainfall anomaly impacts are almost always linked positively with TSS delays to specified target thresholds; iii) the most consistent climate to ripening anomalies relationships were exhibited during the warmest month (August) and during late spring May-to-June bimester and iv) the strength of the significance (higher coefficient of determination), regardless of the sign, between TSS anomalies and climate indicators increases steadily from early ripening thresholds, at early season stages, towards late-ripening thresholds indicating that the weather anomalies at maturity are the most influential in determining berry TSS advances or delays at maturity.

In agreement with recent reports by Costa *et al.* (2020) and Parker *et al.* (2020), these results showed that total soluble solid accumulations were stimulated by anomalous temperatures at véraison and later. This result was observed in terms of potential alcohol increments over a longer period (50 years) by Bécart *et al.* (2022) with respect to the present study (13 years). Regarding the implications of sugar content for the potential alcohol content of the resulting wine, the concentration of TSS is a straightforward and reliable marker for the progress of ripening (Bonada and Sadras, 2015). Common results, indeed, indicate that the Véraison-Harvest phase has an undoubtedly dominant effect on sugar maturity as well as potential alcohol at harvest. This is probably because very high temperatures were recorded in both studies and, even with some differences due to cultivar characteristics, just after véraison during August.

3. Development of a modelling framework

While being empirical, the dataset obtained in this research (4 cultivars × 3 ripening parameters × 13 years) provides for the development of an innovative modelling framework that enables a wide range of potential advantages. Conceptually, from the analysis of data in retrospect, the aims are to develop new agronomical and climate-change-related questions and hypotheses. The results presented herein provide an innovative and useful instrument that can be potentially implemented into smart decision support systems or, even better, process-based models to support management decisions for backward agronomic assessments and future impact forecasts. By using the relationships proposed in the present study, as the season progresses and the grape ripening process, careful monitoring of the weather conditions in relation to the average time interval makes it possible to assess possible advances or delays of ripening with significant advance.

By using the slope-analysis concept proposed in the present study, accurate analysis of the slopes of the relationships between climate and ripening anomalies are dynamically produced and potentially kept updated using the modelling anomaly framework, which may allow for the use of predictive algorithms that can be developed to better characterise future vintages by forecasting a grape maturity profile or a potential advance/delay in the ripening. Wine regions consortia, large wineries, or cooperatives should take advantage of these results in the management of the ‘harvest-window’ opening dates, particularly in those wine regions where several grapevine cultivars are cultivated and seasonal anomalies may cause harvest windows to compress across cultivars. Faced with climate change, this represents an interesting tool to better implement the most suitable management strategies for the ripening period.

For each ripening variable, including TSS, TA and berry pH, the present study proposed consistent relationships between climate and ripening anomalies. This analysis concept can be easily implemented for all winemakers who want to control the level of ripeness of grape and the quality parameters, plan any extraordinary crop operation (such as emergency irrigation or canopy modifications) and, above all, determine the best time to harvest. The definition of the best window for harvesting cannot consider only single ripening variables but, on the contrary, a balance among them. Thus combining the information retrieved by the three ripening variables, or even better, including new ones such as malic acid (white cultivars) and total polyphenols and anthocyanins (red cultivars), represents a key issue to be addressed in the nearest future using multiple linear regression procedures or supervised learning algorithms, such as random forest method. A limit of the present study is represented by not considering the changes in grapevine phenology in the calculations of the climate indicators and solely focusing on calendar-based time intervals (month, bimester). Future research should be undertaken on the current issue to implement the vine's phenological phases into the present modelling framework allowing to consider the effects of climatic anomalies on the real growth periods of the vines. In addition, a further study with more focus on the introduction of a spatially explicit variability characterisation of the relationships between climate and ripening anomalies is recommended.

CONCLUSION

The present study reports a first characterisation of the influences of climate change on grapevine ripening dynamics on four major winegrape cultivars. Using a 13-year database of ripening and climate data for the period 2009–2021, this study presents the development of a modelling framework on the relationships between climate and ripening anomalies seeking to contribute to the understanding of climate change impacts on vineyards. While regression analyses between anomalous maturity thresholds and climate indicators confirm several known relationships, some new findings and a new methodology are proposed. The application of the modelling framework proposed in the present study may allow the use of predictive algorithms developed to better characterise future vintages by forecasting a grape maturity profile or a potential advance/delay in the ripening.

A deep interaction between the vine and the surrounding environment passes through the knowledge and excellent use of the physical factors of each wine region. The optimisation of the quality and health of grape production must therefore be based on deep knowledge of climates, updated by current climate change, and must be oriented towards winegrowing choices and management practices adapted to the changing characteristics of the sites.

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