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Review

Major threats caused by climate change to grapevine

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Abstract: The main worrying feature of climate change is its rapid evolution, in extent and variation, becoming less and less predictable. In this paper, we have reviewed the available literature and elaborated original data to outline how climate change will affect the grapevine cultivation and wine quality. We start by discussing which features of climate change will impact grapevine production most. The effects of heatwaves, air and soil temperature, extreme rainfall events, atmospheric evaporative demand, wildfires, and smoke are addressed. An increased frequency and intensity of heat waves since 2010 is shown in four grapevine production areas of Northern Italy. The focus then shifts to the impacts of the predicted increase in temperature and drought on frost risks, grapevine phenology, yield, berry quality and water needs as well as vine and vineyard carbon budgets. Climate change will challenge the achievement of current yields and wine quality as well as the ability of vineyards to sequester atmospheric carbon, but such effects will likely depend on the characteristics of the growing environments and on the varieties present. Climate change-related threats to grapevine call for a rapid implementation of adaptation strategies.

Keywords: berry quality; climate change; drought; grapevine; heat waves; intense rainfall; phenology.

1. Introduction

The concept of climate relies on statistics to define the average conditions of the atmosphere (temperature, rainfall, wind, etc.) in a specific region and season but, necessarily, also deals with the intrinsic variability of these quantities, which in turn must be characterized and quantified. A current and extremely worrying feature of climate change is its own evolution, in extent and variation, becoming less and less predictable (Olonscheck et al., 2021). Today, in addition to the shift of the average values, we are also witnessing a sudden increase in their variability (van der Wiel and Bintanja, 2021). The climate appears to have lost its "stationarity" (Milly et al., 2008), which is extremely worrying also due to the new stresses that it entails for grapevine cultivation. All of this makes prospective forecasting difficult and may nullify the few adaptation or mitigation options that currently seem available.

2. How climate change is affecting the crop environment

2.1. Temperature and heatwaves

According to the 6th IPCC report on Climate change (2023), global surface temperature was 1.09 °C higher in 2011-2020 than 1850-1900, with larger increases on average over land (1.59 °C) than over the ocean (0.88 °C). Global surface temperature has increased faster since 1970 than in any other 50-year period within at least the last 2000 years. Such effects are mainly traced back to the increase of well-mixed greenhouse gases (GHGs).

An effect of the raised mean annual temperature caused by global warming is the altered frequency of extreme climatic events such as heatwaves (Frank et al., 2015; IPCC, 2012). The specific definition of heatwaves, however, depends on the index used for their identification, which often depends on the goal of the analysis. The Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDI), established as part of a joint project between the World Meteorological Organization Commission on Climatology and the World Climate Research Programme, developed a comprehensive set of 17 indices related to extreme temperature events (Alexander et al., 2006 in Perkins, 2015). Many of these use percentile or range-based methods that allow for the calculation of relative extremes at a local scale, overcoming the flexibility issue faced by global absolute threshold methods (e.g.: the Heatwave Duration Index), which have limited applicability in certain climatic contexts (Perkins, 2011). The CTX90pct index, which is used in this study, identifies heatwaves as periods with a duration ≥3 days during which the maximum daily temperature is greater than the 90th percentile of maximums for that day of the year, as calculated from local air temperature datasets of varying length (Perkins and Alexander, 2013).

Regardless of the identification method, there is consensus that both the overall incidence, duration and severity of heatwaves is increasing (Ganguly et al., 2009; Perkins et al., 2012; Russo et al., 2014). The coolest summers of the period 1992-2022 in central Europe exceed the average summer temperatures of the preceding three decades (Domeisen et al., 2023). Although in 2003 there was one of the worst documented heatwaves in European history (Beniston, 2004; Cristofanelli et al., 2007; Munari, 2011), the year 2019 was the first in which measured temperatures overcame 45 °C in France and 40 °C in Belgium and the Netherlands (Sousa et al., 2020). At the time of writing (July 2023) some Southern Italian regions and several European countries located at the northern side of the Mediterranean Sea, such as Greece, are undergoing a long period (>10 days) of exceptionally high temperatures (>40 °C), caused by the presence of an anticyclone coming from Africa. This trend is not explicable without considering anthropogenic activities, and is largely attributed to the temperature increase due to global warming (IPCC, 2023; Marx et al., 2021). Consequently, under current climate projection scenarios, it is expected to continue throughout the 21st century (Meehl and Tebaldi, 2004; Argüeso et al., 2016). Lhotka et al. (2018) estimated that in the next three decades Central European heatwaves would double in frequency relative to the period 1970-1999, reaching 3-4 heatwaves per summer in 2070-2099 with a much higher incidence of severe heatwaves. This can be expected to pose numerous risks to viticulture. With the aim to understand the situation in Northeastern Italy, we have analysed datasets of average and maximum temperatures recorded in grape-growing districts within the provinces of Bolzano, Udine, Venezia, from 1995 to 2022, as well as in the Province of Brescia from 2002 to 2022. The CTX90pct index was used to identify the heat wave occurrence: for each location, we calculated the minimum and maximum peak temperature (Tmax) of each summer day (June-Aug) across all the years of data available. These values were used to define the daily 90th percentile of Tmax, which was then averaged using a centred moving window spanning 15 days. Tmax values for each summer day in the historical period were then compared with the 90th percentile threshold and a heat wave event was identified whenever values were above the threshold for three consecutive days (Zanotelli et al., 2022). Results are shown in Figure 1, where the number (number of piled bars), length (height of each piled bar) and the intensity (colour of the bars) of the HWs for each year in that period are shown. When no bars are associated with a year, no heat waves were recorded. Apart from 2003 (and a few other sporadic years), most HWs occurred in the last decade, where they took place almost every year. With very few exceptions, in all sites the average summer temperature has been always above the average of the historical series from 2016 on (Figure 1).

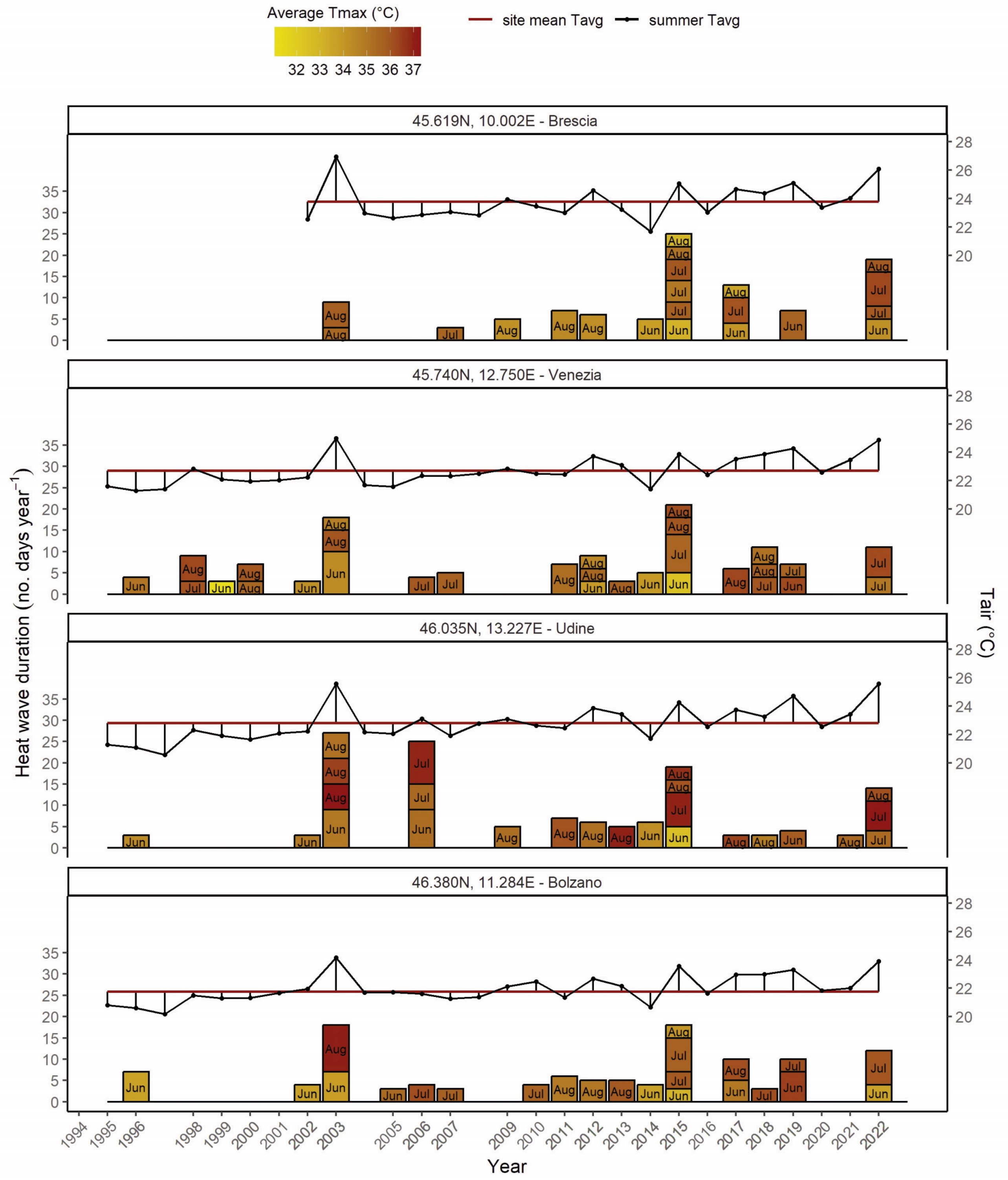

Figure 1. A yearly summary of HWs occurring in summer (June - August) between 1995 (or 2002 in the case of Brescia) and 2022. Column height indicates the duration (in days) of each individual HW and colour indicates the intensity, i.e. the average maximum daily temperature that occurred within the HW. The red lines indicate the mean summer temperature averaged across the period, while the black lines depict the difference between the mean annual summer temperature and the average of the period.

2.2. Evaporative demand, rainfall and drought

In general, the air temperature increase is expected to raise the atmospheric evaporative demand and accelerate the global water cycle (Allan et al., 1998). As a result, the water vapour content in the atmosphere should also increase according to the Clausius-Clapeyron law (Brutsaert, 2017; Adam et al, 2023). However, some evidence indicates a global reduction of both non-water limited evaporation, such as that measured by pans (Roderick and Farquhar, 2002), and evapotranspiration from unmanaged ecosystems (Jung et al., 2010). Evapotranspiration will exhibit a strong regional variability, with water-limited situations increasingly frequent, even in cool- or mild-climate viticulture (Schultz, 2017). Likely, scale effects play a major role and complicate feedbacks reflected in overall water fluxes (Szilagyi and Jozsa, 2018). In any case, it is very likely that irrigation requirements will rise, gradually causing conflicts among different societal actors and users (Liu et al., 2022). Thus, further research to precisely gauge actual water consumption and irrigation requirements also in vineyards will be highly critical and should be implemented in a timely fashion.

Climate change modifies the water cycle, with severe consequences for grapevine cultivation all over the world. Data and projections indicate that several European countries and the entire Mediterranean region will face an increase in land evapotranspiration associated with global warming during the twenty-first century (Barcikowska et al., 2020; Mariotti et al., 2015). Projections for evapotranspiration indicate that the greatest increase will occur in the wet season, while in the dry season there will be an increase only in Central and Northern Europe (Mariotti et al., 2008). The area of the Mediterranean basin is in fact already experiencing summer drought periods, but a further rise in the evapotranspiration is unlikely (Kurnik et al., 2015).

The rainfall projections resulting from different models are quite incoherent and show different variations across territories (Jin et al., 2010; Kaspar-Ott et al., 2019; Mariotti et al., 2015, 2008). Considering Europe and in particular the Mediterranean basin, the greatest decrease in rainfall should occur in Central European, Southern European and the Mediterranean area, while in Northern Europe an augmented average annual rainfall is expected. The predicted seasonal distribution of precipitation for the 21st century indicates that, in most European countries, the greatest reduction in rainfall will happen in the wet season, with minor differences in the dry season (Kaspar-Ott et al., 2019; Mariotti et al., 2008). Rainfall forecast models in Europe identify a longitudinally distributed belt below which this reduction in wet season rainfall is expected. The major part is likely to occur below 42°N, with the greatest decrease at 35°N (Jin et al., 2010; Bucchignani et al., 2016, Giorgi and Lionello, 2008). Differences between predictions are mostly due to the resolution and structure of the models applied (Kaspar-Ott et al., 2019; Paeth et al., 2017). Forecasts for Italy hold true to this, suggesting that above the 42nd parallel, rainfall might increase in the wet season, while the more southern areas are expected to become drier (Coppola and Giorgi 2010).

Looking at the forecasts of the difference between precipitation and evaporation (E-P), it can be seen that the division at the 42 parallel is still present in the wet season, while the increase of E-P in the dry season is rising throughout Europe and the Mediterranean basin (Alpert et al., 2015).

2.3. Intense rainfall erosion and waterlogging

Steep-slope vineyards are widely distributed in the Mediterranean region and have a pivotal role in wine production, economic development, and cultural heritage. Nevertheless, they are threatened by climate change not only in terms of long-lasting droughts, but also as a consequence of heavy rainfalls (Tarolli et al., 2023), which can cause severe soil erosion (Comino, 2018; Prosdocimi et al., 2016). In Italy, vineyards have a long record of continuous runoff and solid transport monitoring, also in relation to soil management (Biddoccu et al., 2014; Biddoccu et al., 2017; Biddoccu et al., 2020). Particularly interesting is the recent work by Zollo et al. (2016), which presents a series of possible future climate scenarios in Italy according to the COSMO-CLM regional climate model. In Veneto region, an increase of 21% in the intensity of average precipitation and of 28% in the intensity of extreme precipitation is expected. A study done by Sofia et al. (2017) analyses one hundred years of flooding in Veneto (1910-2010), linking (and quantifying) climatic factors, urbanisation processes and flood dynamics on a regional scale for the first time. The study shows how short-term intense precipitation increased compared to the total precipitation observed, with an intensification towards the entire range of foothills, from east to west. Considering that in these areas of the Veneto region grapevines are grown on steeply sloping surfaces, the resulting picture is particularly critical.

While high rainfall intensities exacerbate the risk of erosion in hilly areas (Pijl et al., 2022), disrupting several historical landscapes, profound consequences on croplands are also experienced in the flat terrain of plains. Most drainage systems in the lowlands today are clearly becoming inadequate for handling high rainstorm surges, resulting in frequent waterlogging conditions (Straffelini et al., 2021). Viticulture is urgently called to better handle hydrological aspects as well as to guarantee effective rainfall infiltration and safe water management, promoting simultaneously its storage at greater depths. Agrometeorological networks should also adapt to this new regime, taking advantage of modern measurement and processing capabilities to better study transient phenomena. Additionally, measurements of actual rainfall erosivity can be obtained by disdrometers (instruments which measure rain drop diameter, number, and falling speed) (Biddoccu et al., 2017). In Figure 2, an example is reported of an improved, high frequency recording of rainfall events implemented by the University of Padova, designed to provide high resolution rainfall temporal dynamics which can be used to interpret infiltration and runoff processes in vineyards. Often, rainfall events exceed the critical value of 60 mm/h, a threshold which is sometime referred to as “torrential rainfall” (Llasat, 2001), promoting runoff and causing erosion even on medium-slope vineyards as shown in Figure 3.

2.4. Wildfires and Smoke

Wildfires or vegetation fires in general release approximately 1.6-2.8 gigatonnes of carbon into the atmosphere, which is equivalent to approximately 25-30% of the annual carbon emissions derived from fossil fuel consumption (Van Der Werf et al., 2010; Bond et al., 2012). Global warming is increasing the incidence and the severity of wildfires across the world (Pausas and Keeley, 2021) due to effects of

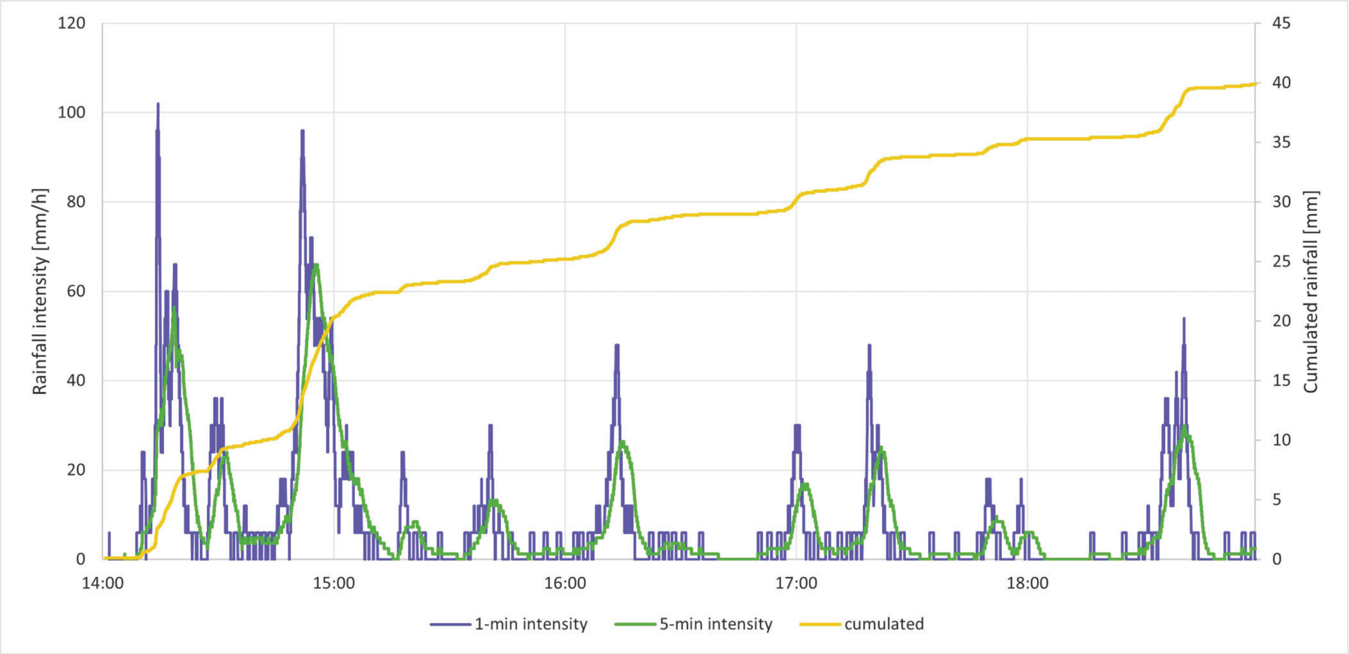

Figure 2. Example of high-frequency recording of rainfall rate in Soave (VR).

Figure 3. Effect of an intense rain event on a recently planted medium-slope vineyard near Conegliano (source: Paolo Sivilotti).

climate change such as drought, increased wind intensity, and heatwaves leading to favourable conditions for fires (Jolly et al., 2015). Available forecast models suggest an increase in wildfire events by the end of the 21st century (Pausas and Keeley, 2021; Shvidenko and Schepaschenko, 2013), which is also likely to play a role in the distribution and migration of plant species (Flannigan et al., 2000). In addition to the environmental effects, the expected fires affect a large part of the population due to air pollution. It has been estimated that in North America more than 80 million individuals will be exposed to a significantly more fine-particulate matter derived from wildfires by the half of the 21st century (Liu et al., 2016). In Europe, wildfires occur mainly in the Mediterranean region, which is characterised by hot, dry, and often windy summers as is typical of coastal areas (San-Miguel-Ayanz et al., 2012). Interestingly, in a data analysis on fires in the years 1980–2013 (34 years), forest fires in Spain have decreased, despite an increase in related risk factors driven by climate change (Urbieta et al., 2019). This result derives from an increase in fire prevention resources, indicating that the anthropic component is always a fundamental factor in the incidence of fires (Urbieta et al., 2019).

In addition to the direct effects of fires, one of the major concerns for crops is linked to smoke taint due to fires near the cultivated areas (Mirabelli-Montan et al., 2021). When vegetation burns in a wildfire, it releases numerous gases (mainly NO_2, CO, CO_2, and SO_2), solid particles deriving from combustion such as ashes, and several type of volatile phenols (Kennison et al., 2009; Ristic et al., 2016; Summerson et al., 2021). The last category is generated by the combustion of lignin, a structural component of woody plants, the pyrolysis of which produces a diverse range of smaller molecules like guaiacol, syringol, and their respective derivatives (Kelly et al., 2012). These compounds are responsible for the charred and smoky aroma that can be present in crops grown near wildfires (Kelly et al., 2012). The smoke taint can be detrimental to the quality, particularly in the case of wine, whose flavour and aroma may be strongly altered by undesirable smoky elements (Bilogrevic et al., 2023). In grapevines, the volatile phenolic compounds present in the smoke are absorbed by leaves and fruit, where they are glycosylated to form glycoconjugates (Hayasaka et al., 2010). The phenolic compounds remain stabilised in this form until they are released during the fermentation process, leading to the wine's subsequent smoky aroma (Kennison et al., 2009; Mayr et al., 2014). With the augmented wildfire frequency associated with global warming, the wine smoke taint phenomena will be a possible limitation in some geographical areas.

3. Impact of climate change on grape production and on vineyard ecosystem services

3.1. Frost risk

Spring (also called "late") frost is a major climatic threat for several crops, including grapevines, as they might occur during or immediately after bud burst, leading to subsequent production losses. In some viticultural districts, vines are cultivated in hilly areas, making them less prone to radiation-driven spring frosts. Nevertheless, they are occasionally hit by advection frosts as was the case in April 2017 in Trentino-Alto Adige. Changes in frequency and intensity of frost risk due to climate changes will be likely region-dependent (Ru et al., 2023, Pfleiderer et al., 2019), with some districts becoming severely affected (Leolini et al., 2018).

Using datasets of minimum air temperature from the province of Udine, we analysed frost occurrence in these areas. As expected, the number of frost events in March and April (those in February are not shown as plants are still dormant in this period) largely varied from year to year (Figure 4), with no clearly visible trend over time. Fewer frost events were present in the period 2014-17, but their occurrence subsequently recovered to values close to the averages of the whole period, in accordance with recent patterns observed by Chen et al. (2023).

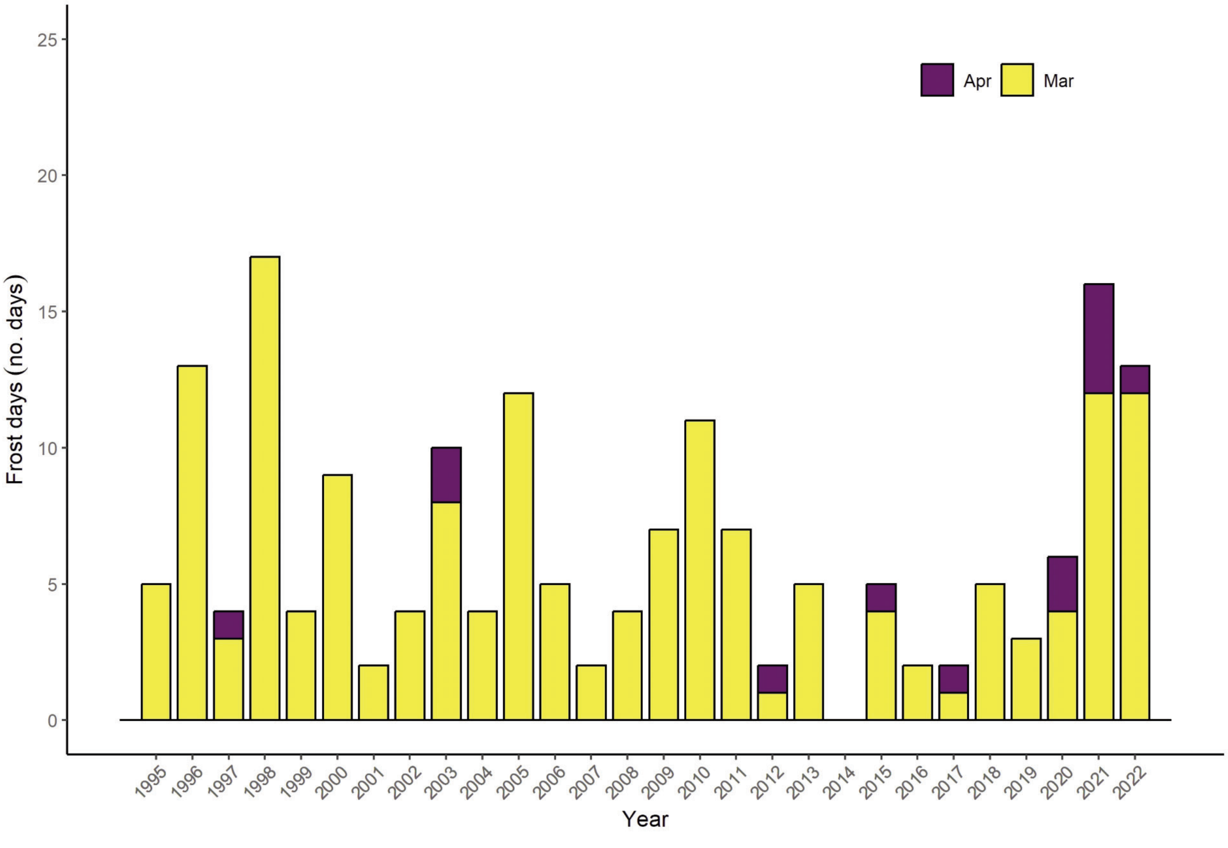

Figure 4. Number of frost days (nights) in the province of Udine (46.035N-13.227E) from 1995 to 2022. During frost nights, the air temperature at 2 m height reached 0 °C or lower values (dry-bulb Temperature). (Weather data downloaded fron ARPA FVG-OSMER, http://www.meteo.fvg.it)

On the contrary, analysis of the temperatures recorded in the province of Bolzano and Udine between March and April revealed that, interannual fluctuations notwithstanding, there has been a faster accumulation of growing degree days (GDD) for grapevines (active temperature = 10 °C) across the considered period (Table 1 and Figure 5), with rate of +1.9-2.0 GDD year^{-1}. However, there are clear exceptions to this trend, such as the years 2021 and 2022, when accumulated GDD was in line with the 1995-2020 average. Cicogna et al. (2021) reported that the date of bud burst of Pinot blanc in Friuli

Table 1. Parameters of simple linear regression of "GDD" (Figure 5, Y axis) versus "year" (Fig. 5, X axis), considering all years available.

Site	Slope (°C yr^{-1})	Intercept (°C)	Adjusted R^2
Bolzano	1.90***	-3702.50***	0.327486
Udine	2.02*	-3936.99*	0.125896

Significance codes: ***p-value < 0.001, *p-value < 0.05.

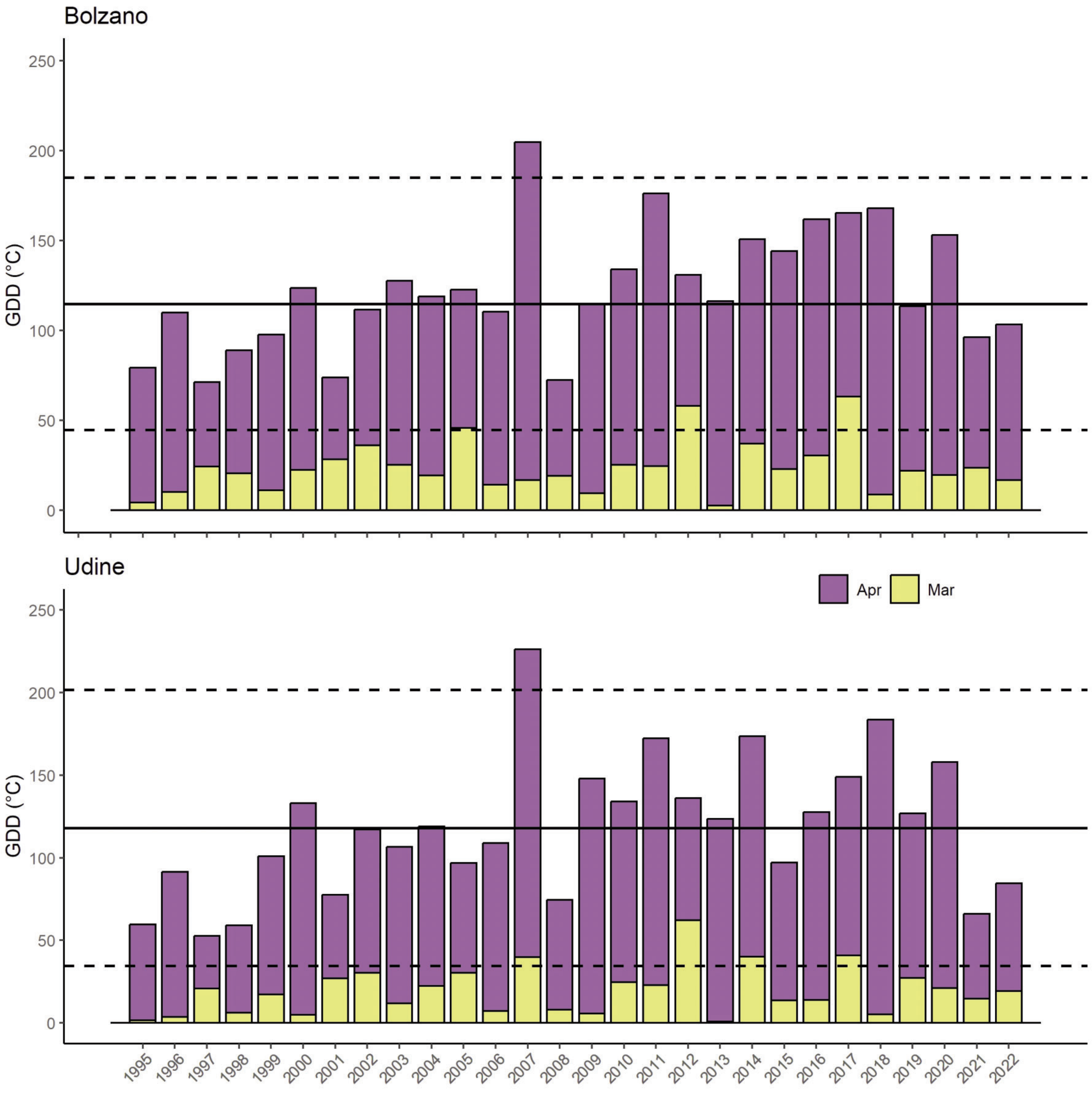

Figure 5. Growing Degree Days (GDD) accumulation in March and April calculated for grapevines in the Province of Bolzano (46.380N-11.284E) and Udine (46.035N-13.227E). GDD were determined using an active temperature of 10 °C. The solid horizontal line indicates the mean GDD at each site

Venezia Giulia was earlier in 2021 than in 2000, and demonstrated that the accumulation of approximately 120 GDD in each season was needed to reach this phenological stage. Several studies have shown an advancement in bud break date in recent years (Ruml et al., 2016; Martínez-Lüscher et al., 2015, Koch and Oehl, 2018), confirming the potential risks for frost damages in future years and the need for precise monitoring of climate variability in the vineyards.

3.2. Phenological shift

Due to the rising temperatures, the upcoming climate change will lessen the chilling accumulation in several locations. As a result, in the future there will be fewer genotypes suited to be successfully cultivated in warm areas. In some temperate regions, a discernible decline in chilling accumulation has already been observed in recent years (Baldocchi and Wong, 2008; Luedeling et al., 2009). Grapevine is considered a low chill requirement species, despite its tendency to burst and flower rather late (Mullins et al., 1992). Guo et al. (2011) have documented the negative impact of recurrent high-temperature fluctuations on the process of endodormancy. Anzanello et al. (2014) have also pointed out that elevated temperatures alternated with cold spells can lead to significant delays and irregularities in budburst. This phenomenon occurs because the high temperatures can counteract the accumulated chilling effect. To minimise this problem, Fila et al. (2012, 2014) calibrated modelling solutions for predicting grapevine phenology and budburst under present and future climate scenarios, with high accuracy.

Phenological processes such as flowering and leaf development are strongly temperature driven. In an analysis of 542 European species, 78% of them have reportedly experienced an advancement in phenological progression due to climate change, with an estimated shift of 2-5 days per decade (Menzel et al., 2006). Both rising temperatures and drought are considered to influence harvest time and wine quality (Camps and Ramos, 2012). In grapevines, the effects of drought on phenological shifting are still a matter of debate (Cook and Wolkovich, 2016; Webb et al., 2012), while there is a body of evidence showing that temperature changes will likely anticipate not only bud burst, but also flowering, veraison and ripening (Ramos and Yuste, 2023; Webb et al., 2012). In Spain, for example, it has been estimated that flowering will be anticipated by 7 days by 2050 in the cultivars Verdejo, Viura and Sauvignon Blanc (Ramos and Yuste, 2023).

Increasing temperatures are directly connected to fruit ripening, which explains the early harvests observed in the main wine-growing regions worldwide (Webb et al., 2012). In contrast, berry ripening is more affected by the duration of the period between budburst and flowering than by the temperature regime between flowering-veraison or veraison-maturation (Cameron et al., 2022). Historical phenological records at Conegliano (Italy) indicate that the main phenological phases were significantly anticipated by 13-19 days from 1964 to 2009, with the exception of budbreak (Tomasi et al., 2011). This shift was strongly correlated with the increasing seasonal temperatures during that period, which rose by 2.0 °C, resulting in an 8-day shift in phenology per 1.0 °C increase in temperature (Tomasi et al., 2011). Mathematical models have been developed and validated to assess phenological shift of grapevine, even under predicted climate change scenarios (Fila et al., 2014).

The University of Udine collected phenological data over the last 16 years in the “Friuli Colli Orientali” area. The date of budbreak, flowering and ripening of Pinot gris and Sauvignon blanc were monitored and the temporal distance between budbreak and flowering as well as between flowering and ripening was calculated (Figure 6). The trend did not show any significant relationship between the phenological phases duration and the years, probably due to the short period of time of the analysis (Table 2). Despite the fact that no clear trend over time was visible, the ripening phase occurred very early during the growing seasons of 2018 and 2022 (96 and 88 days after budbreak respectively in cv. Pinot gris and 95 and 88 days for Sauvignon blanc), in line with the exceptionally short period between bud burst and flowering (Cameron et al., 2022).

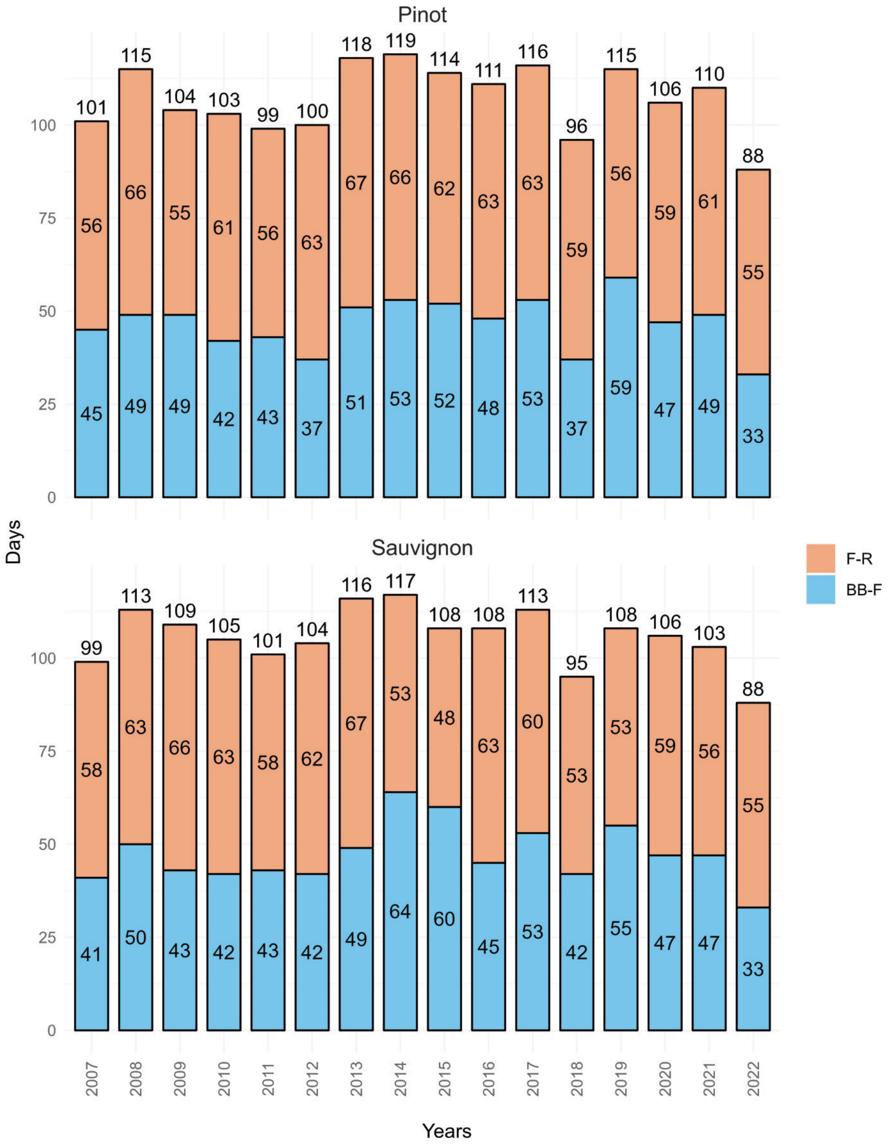

Figure 6. Length (days) of the period between the phenological phases: "bud break - flowering" (BB-F),"flowering - ripening" (F-R) (left y-axis). Numbers above the bars indicates the total length (days) between "bud break and ripening" (BB-R). The data refer to the period 2007-2022 and were collected in the "Friuli Colli Orientali" area (Friuli Venezia Giulia, Italy) for the cultivars Pinot gris (top) and Sauvignon blanc (bottom).

Table 2. Parameters of simple linear regression between the length (days) of the main phenological stages (period between the phenological phases: "bud break - flowering" (BB-F),"flowering - ripening" (F-R)) vs years, considering all years available.

Cultivar	Phenology	Slope (days yr^{-1})	Intercept (days)	Adjusted R^2
Pinot	BB-R	-0.14 ns[1]	394 ns	-0.06
	BB-F	-0.031 ns	108 ns	-0.07
	F-R	-0.11 ns	285 ns	-0.05
Sauvignon	BB-R	-0.49 ns	1086 ns	0.02
	BB-F	0.05 ns	53 ns	-0.07
	F-R	-0.53 ns	1139 ns	0.17

1 ns= not significant

3.3. Carbon budget and plant physiology

The effects of temperature on plant organs (leaves, flowers, fruits, etc.) are the complex results of physical and physiological exchange processes that profoundly affect their growth and development. In fact, the limited thermoregulation capacity of plants exposes their metabolism to continuous variations in temperature, which does not always remain within optimal ranges. If transpiration takes place without restriction, the temperature of the vegetation can be several degrees lower than that of the air, but this ability cannot prevent it from reaching high or even lethal values when high ambient temperatures persist for long periods. In this regard, the summer of 2022, with the air temperature that abundantly and continuously exceeded 35 °C in the plains of northern Italy, marked another worrying evolution of the climate, subjecting grapevines to stress levels that have never been previously reached in that area and resulting in significant production losses (Veneto Agricoltura, 2022). Grapevine varieties differ as to their adaptation to concurrent heat and drought stress. While leaves of Montepulciano promptly tend to close their stomata and save water, those of Sangiovese show morpho-biochemical and physiological features that optimize the whole-vine carbon gain under multiple stresses (Palliotti et al., 2009; Palliotti et al., 2015).

The thermal stress that occurred in this period had exceptional features, which can be interpreted by recalling the physiological bases of grapevine productivity. Growth depends above all on photosynthesis, which is itself a chain of reactions, all inevitably conditioned by the temperature of the leaf. The overall efficiency of photosynthesis is, therefore, strongly influenced by leaf temperature, with optimal values for temperate species around 25-27 °C (Tombesi at al., 2019; Huang at al., 2019) and up to 30 °C in hotter climates (Greer and Weedon, 2012). The end products of photosynthesis (carbohydrates) are transferred, to actively growing organs or accumulated in specific tissues. High night temperature decreases the translocation of carbohydrates to grapevine leaves (Tombesi et al., 2019). In this “administration” of the carbohydrates produced during the day, the plant observes priorities and typically optimizes their distribution to maximize the growth of the individual. In addition to synthesis, carbohydrate utilization processes - in particular respiration - also inevitably occur in the plant and are necessary for the maintenance of the vital functions of cells, tissues, and organs. Indeed, the complexity of every living cell requires a constant renewal of structures and metabolic capacities, which can easily consume 30-40% (Hernandez-Mondes et al., 2022) of what the plant synthesizes. Growth, therefore, is determined both by the capacity for synthesis and by the needs related to maintenance. This balance between inputs (photosynthesis) and outputs (respiration) strongly depends on the physiological conditions of the plant and environmental variables.

Temperature, one of the environmental factors that most directly affect plant productivity, has different effects on photosynthesis and respiration: the former rarely remains active above 40 °C (Galat Giorgi et al., 2019), while the latter continues to rise even beyond this threshold, consuming an increasing share of the acquired resources (Hernandez-Mondes et al., 2022). The net production, therefore, grows up to 25-30 °C, but then drops rapidly, vanishing at around 40 °C. Beyond this limit, it is expected that grapevines survive, but at the expense of reserves. Even the respiratory metabolism decreases at high temperatures, ceasing completely towards 50 °C (the temperature at which the cells undergo irreversible damage and die).

3.4. Water requirements

Irrigation water requirements are influenced by various factors that interact with vegetation present in the vineyard (Villalobos and Fereres, 2016). The evapotranspiration (ET), which is the sum of the evaporation and transpiration components, drives to a great extent the crop irrigation requirements, which in turn are influenced by both abiotic and biotic factors. The abiotic factors include soil water availability, solar radiation, wind speed, air temperature, relative humidity, and precipitation (Allen et al., 1998). The biotic factors, on the other hand, include canopy structure (Ringgaard et al., 2014), the degree of coupling between the canopy and atmosphere (Jiao et al., 2018), and leaf area index (LAI) (Mancha et al., 2017).

Air temperature and solar radiation are the main drivers of transpiration (Zhao et al., 2018), provided that soil water is “readily available”. Elevated air temperatures influence stomatal control, affecting the water fluxes at leaf-, plant-, and ecosystem-scale (Teuling et al., 2010; De Kauwe et al., 2019). Scenarios depicting an increasing ET and diminishing (or erratic) precipitation indicate the increasing difficulty of adequately irrigating grapevines using current technologies. When exposed to high temperatures, in conditions without water restriction, grapevines increase transpiration as shown by Asensio et al. (2022), who registered approximately twice as much daily transpiration (T) in grapevines subjected to 40 °C, compared to well-watered vines exposed to normal summer temperatures. On the contrary, it is expected that non-irrigated crops already experiencing drought will not significantly increase their transpiration rate (Asensio et al., 2022).

Soil water status also affects grapevine behaviour during heat wave periods (Redondo-Gómez 2013) since leaf transpiration provides a cooling effect, thus counteracting the impact of high external temperatures. Indeed, irrigated grapevines subjected to heat waves managed to recover normal physiological functions, while plants that faced combined heat and water stress did not (Galat Giorgi et al., 2019, Lehr et al., 2022). Besides the direct effects of high temperature on plant transpiration, there is its exacerbating effect on evaporation, which might threaten agricultural systems via soil water availability during a heat wave event (Asensio et al., 2022).

3.5. Yields and berry quality

Water scarcity and high temperatures due to climate change will likely pose a threat to the yield and berry quality of rainfed grapevines, which comprise the majority of vineyards in Europe (Costa et al., 2016; Zajac et al., 2022). If not severe, drought alone is not expected to have negative effects on berry composition, and sometimes may even be beneficial: under mild water deficit conditions, berries accumulate secondary compounds useful to avoid oxidative damages, which also enhance fruit and wine quality (Albrizio et al., 2023; Duan et al., 2022).

Instead, excessive summer temperatures can inhibit several metabolic pathways, leading to changes in the accumulation of berry metabolites and disrupting the balance between sugar and organic acid composition (Blancquaert et al., 2018, van Leeuwen et al., 2019; van Leeuwen and Darriet, 2016). The effects of high temperatures include the inhibition of the expression of the main genes involved in anthocyanin biosynthesis (Mori et al., 2005), the reduction of anthocyanins and lower concentrations of flavour compounds in berries (Azuma et al., 2012; Venios et al., 2020). Temperatures above 40 °C does not only reduce terpene biosynthesis but also increase their degradation (Loreto and Schnitzler, 2010). Indeed, a Tmax reduction of 2-4 °C around the berries on a hot summer day has been shown to enhance the presence of volatile compounds of cv. Grillo grapes (Scafidi et al., 2013).

Despite the high temperature-driven impairment in sugar accumulation, the final concentration of soluble sugar usually increases in the berry as a consequence of the fruit dehydration, which also affects the final fruit weight and size (Keller, 2010; Mira de Orduña, 2010). The resulting wines therefore have higher concentrations of ethanol and lower levels of volatile compounds (Le Berre et al., 2007; Robinson et al., 2009).

Viticultural regions known for producing high-quality wines are typically found in specific areas with distinctive microclimates which could be altered by global warming, severely affecting product quality (Fraga et al., 2013). An earlier harvest, due to the climate-change derived phenological shift, will likely disadvantage more those varieties with early harvest and favour the late harvest variety in many areas. Wine quality records of the last 100 years in the regions of Bordeaux and Burgundy show how high-quality wines were associated with earlier harvests, favoured by drought conditions and warm temperatures (Cook and Wolkovich, 2016). However, the connection between drought and temperature has been decoupled in the recent years, suggesting that climate change has modified the climatic driver of early grape harvest in this region. Jones (2007) showed how Bordeaux (France) and Napa (USA) wine regions are already at the edge of the optimal growing seasonal temperatures for Cabernet Sauvignon, and a further increase of temperature expected by 2050 will threaten high-quality production. The work of Gambetta and Kurtural (2021) confirms the concern for wine quality in these two regions, suggesting that, while the temperature rise over the last 60 years has initially benefited wine quality, a tipping point has been reached, where further temperature increases are now likely to adversely impact the wine quality. A study conducted in the La Rioja region of Spain examined the impact of varying temperature scenarios on phenology and berry quality. The findings revealed that increasing temperature was associated with a decrease in total acidity and anthocyanin concentrations in the berries (Ramos and Martínez de Toda, 2020), indicating the effect of temperature on harvest timing and the consequent threat to the wine quality.

Heatwaves are often associated with high light intensity and excessive UV radiation, which can result in sunburn damages. This may result in a browning of the berry exocarp and a consequent modification of the berry quality (Gambetta et al., 2021; Rustioni et al., 2014). The increase in solar radiation will likely drive the increase in the severity of sunburn damages in Europe (Wild 2016). The main mechanism through which this occurs is the photooxidation process, whereby high light intensities generate reactive oxygen species (ROS), causing oxidative damages (Rustioni et al., 2014). Therefore, direct exposure of berries to sunlight increases the chances of sunburn on high light intensity days, which will force future changes in canopy management strategies for damage mitigation (Bahr et al., 2021).

3.6. Carbon sequestration

Agricultural systems and land-use changes are responsible for approximately 25% of total anthropogenic emissions of greenhouse gases, a share that increases if the entire food chain is considered (Friedlingstein et al., 2022). Such emissions are partially compensated by the ability of some agricultural systems (under proper management techniques) to sequester atmospheric CO_2 in the soil or biomass. Such systems exhibit a positive balance between the total plant photosynthesis and the sum of the ecosystem respiration and lateral carbon (C) fluxes owing to the removal of plant products (Tiefenbacher et al., 2021). In Italy, studies investigating the role of vineyards in the global carbon budget began quite early relative to other crops (Gianelle et al., 2015), with the first permanent eddy covariance station established in 2005 (Pitacco and Meggio, 2015). Indeed, vineyards and other woody plantations have the potential to provide this type of ecosystem service (Vendrame et al., 2019, Zanotelli et al., 2013, 2015 and 2018), also due the fact that they often include the co-presence of permanent herbaceous groundcover vegetation that may account for a large portion of vineyard net primary production (Callesen et al., 2022) and promotes the build-up of relatively high amounts of soil organic matter (Tezza et al., 2019). This is of relevance to C farming initiatives, most of which recommend cover cropping as a key strategy to increase soil C sequestration and storage. It is still unclear however to what extent such a measure could significantly mitigate the agricultural emissions. In a recent study, Seitz et al. (2022) have indicated that cover crops are a promising option for enhancing soil organic carbon (SOC) stocks in croplands, but their benefits only counteracted 11% of Germany’s annual agricultural greenhouse gas emissions.

Climate change does not increase only atmospheric temperature, but also that of the soil. Schultz (2022) reported an increasing trend of soil temperatures in various vineyards of Southern Germany over the last 40 years, with average summer temperatures (at 50 cm depth) changing from 18 to 22 °C. Such a soil temperature change, in the presence of sufficient moisture, will likely promote higher C turn-over rates, increasing losses of C via heterotrophic respiration (Lloyd & Taylor, 1994). This reduce the ability of ecosystems like vineyards to effectively sequester and store C and may also threaten preexisting SOC stocks (Kirschbaum, 1995), which is where the majority of vineyard C is located (Callesen et al., 2023).

The negative effect of temperature on terrestrial C balance is even more drastic when the marked reduction in photosynthesis relative to plant respiration above a certain threshold is taken into account. At best, the relative impacts of climate variation on soil respiration and net primary productivity may be seen as high inter-annual variation in (positive) net ecosystem production, as observed in vineyards by Vendrame et al. (2019). In more extreme cases, ecosystems may shift from C sink to net source, as occurred during the European heatwave of 2003, when the total C accumulated in Europe over the five preceding years was lost in few months (Ciais et al., 2005). This indicates the vulnerability of C storage and sequestration in terrestrial ecosystems, including vineyards, to a changing and frequently extreme climate.

4. Conclusions

The review of the existing literature and the analysis of our datasets suggest that climate change will likely cause an increase in extreme climatic events and modify numerous climatic characteristics, which will alter the availability of resources and pose a threat to the maintenance of current levels of productivity as well as berry and wine quality. Moreover, climate change will challenge the ability of vineyards to sequester atmospheric carbon. To which extent the climate-related threats will display their adverse impacts likely depends on the characteristics of the growing environments. Climate change-related threats to vineyards require the implementation of adaptation strategies (Gutiérrez-Gamboa et al., 2021), which will include precise monitoring and supply of increasingly limited resources (such as water), the development of suitable management techniques and the availability of new genotypes more adapted to future scenarios.

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