Impact of long-term (1764-2017) air temperature on phenology of cereals and vines in two locations of northern Italy

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Highlights

- *Long-term weather series show how the mean air temperature and its extremes have changed over the years.*
- *Simulation of cereals and perennials phenology using long-term weather series showed a shortening of the growing season and a shift of developmental stages.*
- *The number of days when the air temperature is above the crops' physiological threshold increased, with implications for development and senescence rates.*

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Availability of data and materials: crop models' output, source code, and the R code's for generating the Figures are available upon request.

See online Appendix for additional Tables and Figures.

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Abstract

Understanding how long-term temperature variability affects the phenology of the main agricultural crop is critical to develop targeted adaptation strategies to near and far future climate impacts. The objective of this study was to use crop phenology as a proxy to quantify the impact of a long-term temperature variability series (1764-2017) on a summer cereal crop (maize), spring wheat, winter wheat, and four different vines (perennials) in two locations representative of the main agricultural areas in northern Italy. To develop the phenological models for cereals and grapevines, the minimum (T_{Dmin}) and maximum (T_{Dmax}) daily temperatures for Milano and Bologna, northern Italy, from 1763 to 2017 were used. Results showed that wheat (spring and winter) has experienced a reduction in the growing period of 13 days for each °C of air temperature increase during the growing season. Vernalization requirements of winter wheat indicated that further increase in air temperature will determine a shift towards a supra-optimal range. The subsequent delay in vernalization fulfilment causes the grain filling phase to occur in warmer conditions and will be further shortened with consequences for final yield. Chilling accumulation in vines was fulfilled over the entire period under study with 90% effective chilling.

Introduction

The recent changes in climate patterns, accelerated by anthropogenic factors, have impacted agriculture, a particularly vulnerable sector. The unequivocal warming since the 1950s' has affected the development, growth and yield of major crops (Zhao *et al.*, 2017; Intergovernmental Panel on Climate Change, 2021). Phenology, defined as the timing of life cycle events of plants (Porter and Gawith, 1999; Stucky *et al.*, 2018), is an important determinant of the way crops partition biomass to various organs, and therefore final yield (Asseng *et al.*, 2015) and it is mostly affected by changes in air temperature (Ritchie, 1991).Phenology plays an additional role in plant annual carbon uptake through the onset of growth and senescence (Cleland *et al.*, 2007). The advance or delay of phenological phases in response to climate variation can expose the growth cycle of crops in an unexplored climatic window (Visser and Both, 2005), possibly exposing critical phenological phases to extreme weather events. Several studies report that there are temperature limits beyond which both flowering and fruit set are impaired leading to yield decrease, *e.g.* wheat (Porter and Gawith, 1999), maize, olive (Koubouris *et al.*, 2009; López-Bernal *et al.*, 2018; Moriondo *et al.*, 2019) and vines (Leolini *et al.*, 2018); or a reduction in yield quality (Moriondo *et al.*, 2011a). In this context, plant phenology is one of the factors that can be studied to evaluate the adaptive capacity of a species to global warming (García de Cortázar-Atauri *et al.*, 2009; García de Cortázar-Atauri *et al.*, 2017).

The recent warming trend has impacted grapevine phenology and harvest dates worldwide leading to problems with grape quality, as grapes will have higher sugar concentration and lower acid content (Neethling *et al.*, 2012; Bock *et al.*, 2013; Koch and Oehl, 2018). For cereals, it has been observed that, despite geographical and cultivar differences, temperature effects on phenology lead to variation in final yield (Fatima *et al.*, 2020; Menzel *et al.*, 2020). In particular, projected temperature changes during critical developmental stages, like flowering, will exacerbate the effects of temperature on final production (Moriondo and Bindi, 2006; Moriondo *et al.*, 2011b; Leolini *et al.*, 2018; Webber *et al.*, 2018).

In Southern Europe, the increase in air temperature causes an acceleration in crop phenology and a reduction of the growth period (corresponding to a reduction in solar radiation interception) and crop yield (Ruiz-Ramos *et al.*, 2018). The negative response of yield to the lower number of growing days is also exacerbated by drought and nutritional stresses (depending on soil type), as found in the Mediterranean Basin (Ruiz-Ramos *et al.*, 2018; Cammarano *et al.*, 2019). In Northern Europe, a slight warming will result in a longer growing season and a beneficial period of frost-free conditions. However, future risks of heat-related stress around flowering have been predicted in England and Wales (Semenov, 2008). In this case, a combination of better agronomic practices and breeding can help to offset the negative impact of temperature and rainfall variability. These studies emphasise the role of phenology in estimating the vulnerability of a crop through the study of its interactions with projected climatic changes.

Global climate models (GCM) and regional climate models (RCM) provide coarse and fine spatial resolutions of projected climate trends, respectively. They are useful tools to predict future scenarios, but their use to recreate past temperature patterns has not been successful, especially on the local scale (Moriondo and Bindi, 2006; Moriondo *et al.*, 2013). Conversely, historical long-term weather trends include periods of temperature and precipitation variability which are part of the natural climate system (Luterbacher *et al.*, 2006; Cammarano *et al.*, 2016). Their use in understanding the near-term impacts of climate is justified by the fact that they contain warm and cold periods and will allow better understanding on near-future climate impacts. Being actual climate records, they also preserve the temperature and climatic variability of the study area. In crop phenological models, these datasets can provide crucial information about the behaviour of crops as they experience varying climatic conditions over the examined period (Asseng *et al.*, 2004; Asseng *et al.*, 2011; Webber *et al.*, 2014; Webber *et al.*, 2016). Therefore, past climate information can provide a benchmark for highlighting which cultivars or crop species can be promising for the development of long-term adaptation plans (Cammarano *et al.*, 2016). For example, in the northern regions of Italy, plurisecular time series were used to ascertain the relationship between climate and vegetation, and to improve the quality of yields and compare the results with the observation notes reported in Targioni-Tozzetti (1767), Toaldo (1781) and Schouw (1839).

In many agricultural studies, crop phenology has been used as a proxy for evaluating the impacts of changing air temperature on crops (Asseng *et al.*, 2011; Asseng *et al.*, 2015; Asseng *et al.*, 2017; Zhao *et al.*, 2017). We hypothesise that the study of century-scale long-term temperature variability and its impact on the phenology of important agricultural crops will aid our understanding and the development of targeted adaptation strategies for the near- and far-future. The objective of this study is to use crop phenology as a proxy to quantify the impact of a long-term temperature series (1764-2017) on a summer cereal crop (maize), a spring wheat, a winter wheat, and four different vines (perennials), in two Italian sites, Milano and Bologna.

Materials and methods

Climate data

To develop and validate phenological models for cereals and grapevines, the minimum (T_{min}) and maximum (T_{max}) daily temperatures for Milano and Bologna from 1764 to 2017 were used. Northern Italy has a precipitation regime characterized by the penetration of the Atlantic perturbations in spring and autumn. The summer is hot and tends to be dry, except for some local rains generated in the afternoon by the development of cumulus clouds (Reiter, 1975; Wallén, 1977).

In Milano, the air temperature series for the period 1764-1998 were published by Maugeri *et al.* (2002), while data from 1999 to 2017 were collected from the station of the Meteorological Service of the Italian Air Force (AM) at the Linate airport (45°25′59.66″N and 9°16′56.24″E; 103 m asl). The 1999-2017 weather data were downloaded from the Climate Data Online of the National Centres for Environmental Information (https://www.ncdc.noaa.gov/cdo-web/). The daily temperature extremes were available for the whole 1764-2017 period.

Bologna daily average temperatures (T_{mean}) from 1763 to 1815 were taken from the series reconstructed by Camuffo *et al.* (2017), and the period from 1814 to 2000 by Brunetti *et al.* (2001). The early period of the Bologna series, from 1764 to 1814 missed the daily extremes of temperature T, that can be calculated with models that respect both the average and the variance on the monthly and yearly scales. A methodology has been developed to reconstruct over the calendar year the daily maximum (T_{max}) and minimum (T_{min}) values from the daily mean (T_{mean}). The methodology requires two independent datasets of observed data, one to be used for calibration (*i.e.* to build the model), and another for validation (*i.e.* to validate the model).

The 60-year dataset (1964-2020) taken from the AM station sited at the G. Marconi airport, Borgo Panigale (44°32′7.59″N and 11°17′19.20″E; 37.5 m asl), was used for calibration. The 21-year dataset (2001-2020) taken from the station sited at Sasso Marconi (44°28′22.80″N; 11°14′28.50″E; 275.0 m asl), available in the archives of the Agency for Prevention, Environment and Energy of the Emilia-Romagna Region (ARPAE), was used for validation.

The calibration was performed following the three steps below:

1 for each month of each of the 60 years of the calibration dataset, the monthly average of daily T_{max} (12×60 values) was

calculated;

2 for each day of the calibration dataset, the difference between the daily T maximum and the monthly average of T_{max} of the correspondent year (365×60 values) was calculated. We worked with the difference between the daily T_{max}/T_{min} and the monthly average of T_{max}/T_{min} of the correspondent year to make the method independent from the period selected and to avoid any problems related to the presence of trends;

3 the monthly standard deviation (SD) of these differences (12×60 values) was calculated.

The procedure was repeated for T_{min} (steps 4, 5 and 6). The monthly averages of the differences calculated in 2) and 5) have been interpolated with two polynomial functions; the coefficients of determination, $R^2=0.995$ for T_{max} and $R^2=0.991$ for T_{min}, indicate that the models fit the observed data well. These two functions were then verified against the validation dataset. The steps from 1) to 6) were repeated starting from the calculated data (not the observed). Figure 1 shows the scatter plot of the observed data *versus* the calculated data for T_{max} and for T_{min} at daily level. The coefficients of determination are close to 1: $R^2=0.979$ for T_{max} and $R^2=0.965$ for T_{min} respectively, confirming that the calculated data fit well the observed data. Finally, the monthly standard deviations (SD of the differences calculated in 3) and 6) for the observed and calculated data have been compared (Figure S1). They assume values lower than 0.8°C for T_{max} and lower than 1.2°C for T_{min}, indicating good agreement between the variability of the observed and simulated datasets for both T_{max} and T_{min}.

Daily temperature extremes from 1814 to 2003 were taken from Brunetti *et al.* (2001) who analysed the historical data taken at the Astronomical Observatory of Bologna and the weather station of *Bologna Idrografico* (44°29′58.99″N; 11°20′45.99″E; 84.0 m asl). For this study, the dataset has been extended to 2017 using the records collected from the same weather station taken from the database of ARPAE. Gaps have been filled using the nearby station *Urbana* (44°30′2.71″N; 11°19′43.6″E; 78.0 m asl), also of ARPAE.

The daily mean air temperature was calculated as:

$$T_{mean} = \frac{(T_{max}+T_{min})}{2} \tag{1}$$

Daily values may have some relevant errors; however, errors for monthly averages are lower than 0.6°C and the annual average is accurate (Camuffo, 2002).

Phenological models

Cereals

The development of the cereal crops was simulated using a simple thermal time approach (Ritchie, 1991), in which plant development is assumed to be a function of daily mean temperature alone. Thermal time is calculated from sowing date on a daily basis according to the following approach:

$$Tt = \sum_{i=1}^{n}(T_{mean} - T_b) \quad \text{for } T_b < T_{mean} < T_{cutoff} \tag{2}$$

$$Tt = \sum_{i=1}^{n}(T_{cutoff} - T_b) \quad \text{for } T_{mean} \geq T_{cutoff} \tag{3}$$

where *Tt* is the cumulated thermal time from sowing date to the day *n*, T_{mean} is the mean daily temperature, T_b and T_{cutoff} are the minimum and maximum temperature limits for development, respectively. If $(T_{\text{mean}} - T_b) < 0$, then the thermal accumulation for that day is set to 0. If the mean daily temperature exceeds T_{cutoff}, then T_{mean} is set equal to T_{cutoff} in the calculation of thermal time for that day (Ritchie, 1991).

For the development of a maize (MZ) phenological model, an FAO maize hybrid class 500 was considered. The maize sowing date was assumed to have taken place on day of the year (DOY) 135, which was the mean sowing date of maize in the area of study. Cardinal temperatures for thermal time calculation were T_b=10°C and T_{cutoff}=30°C. The flowering and maturity dates occurred when 780°Cd and 1400°Cd were achieved, respectively (Table S1).

For spring (SW) and winter wheat (WW), medium-cycle varieties were adopted with a total of 900°Cd degree days and 1500°Cd as thermal time (the sum of degree days) for flowering and maturity, respectively (Table S1). T_{cutoff} was set to 30°C for both, while T_b was set to 3°C for spring wheat and 0°C for winter wheat. Sowing date was set on DOY 315 for winter and spring wheat. For winter wheat the accumulation of thermal time started after the vernalization requirement was satisfied. Vernalization is the need of a crop to be exposed to cold temperature before progressing with development. In our calculations, we considered a winter wheat variety with medium vernalization requirements as vernalization was satisfied when 50 days with a mean daily temperature between 3°C and 10°C had occurred.

Grape

The phenological development of grapevine (*Vitis vinifera* L.) was estimated using the UNICHILL model of Chuine *et al.* (2000a). The model is a temperature-driven approach in which the accumulation of chilling units (CU) and forcing units (FU) is used to describe the endo-dormancy release, budbreak, flowering and veraison stages. The dormancy period before budbreak depends on CU and FU. The effect of chilling temperatures was accounted for during the endo-dormancy period in which the buds are dormant. This was due to endogenous factors that varied due to grapevine physiology. The FU were accumulated during the eco-dormancy period where the limitation to bud growth is driven by unfavourable temperature conditions (exogenous factors).

The accumulation of CU was assumed to start from the 1st of

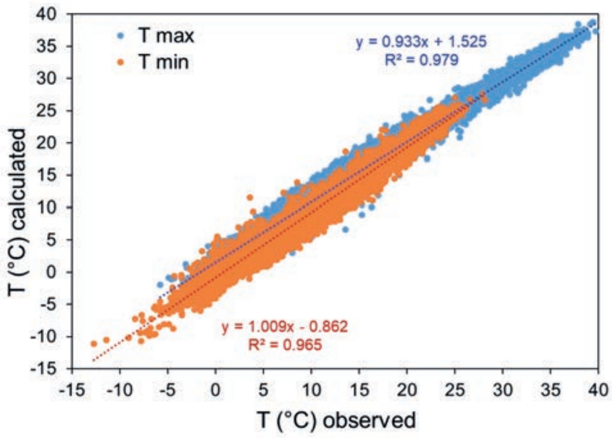

Figure 1. Scatter plot of the daily observed and calculated data for daily maximum (T_{max}) and minimum (T_{min}) temperature.

September, which coincides with the beginning of bud dormancy in temperate zones (Chuine *et al.*, 2000a), until the achievement of the variety-specific chilling requirement (endo-dormancy release). After this stage, the model accounted for the accumulation of FU during the eco-dormancy period until reaching the forcing requirement and budbreak date. When the dormancy period was fulfilled, the flowering and veraison stages were described by accounting for a 'variety-specific' accumulation of FU. The daily rate of CU (Eq. 4) and FU (Eq. 5) are described by the following equations:

$$CU_i = \frac{1}{1+e^{a_c*(T_{mean}-C_c)^2+b_c*(T_{mean}-C_c)}} \qquad (4)$$

$$FU_i = \frac{1}{1+e^{b_f*(T_{mean}-C_f)}} \qquad (5)$$

where CU_i and FU_i are the CU and FU's rates at day i, respectively; T_{mean} is the daily mean air temperature, and a_c, b_c, c_c, b_f and c_f are the empirical parameters of the equations. In this study, we used the parameterizations obtained by Fila (2012) on an integrated dataset including phenological data of field observations and data derived by a growth chamber experiment with forced cuttings (calibration B). These parameterizations refer to four different precocity levels of grapevine phenology represented by very-early and early (Glera and Chardonnay), medium (Merlot) and late (Cabernet Sauvignon) varieties as showed in Table S2 and Figure S2 (Fila, 2012).

Results

The long-term annual mean air temperature showed different patterns for Bologna and Milano (Figure 2). Overall, a swinging trend can be recognized, regardless of the average temporal window, more evident for Bologna than Milano (Figure 2). In addition, for each location there was a clear increase in mean air temperature starting from the 1980s onwards, as reported in spring months in Figure 2. The monthly average temperature trends for Milano and Bologna from 1764 to 2017 were characterized by high variability (Figure S3). In particular, March and April had a different degrees of increased air temperature with respect to the long-term trend (Figure S4). However, at the same location, other months (*e.g.* Jan, Feb) did not show similar patterns (Figure S3).

The density distribution of the mean temperatures for all months in Bologna and Milano are shown in Figures 3 and 4. Each bell corresponded to a recent 30-year reference period: i)1960-1990; ii) 1980-2010; iii) 1987-2017, the vertical dashed line indicates the yearly mean air temperature over the 1764-2017 period and the dotted vertical line the monthly mean air temperature over the same period. Overall, it is interesting to note that for both locations the distributions related to the months of Apr and Oct were not dissimilar from the long-term mean monthly temperature that was the 1764-2017 period (Figures 3 and 4). In both locations, the 1960-1990 period shows a similar mean temperature to the period 1764-2017, but the mean over the 1987-2017 period is about 1.4°C higher than 1764-2017 (Figures 3 and 4). In Milano, the difference between the 1987-2017 period and the others was more evident than in Bologna; for example, in Mar and Dec the 1987-2017 mean is 2.0°C and 1.7°C higher than the monthly averages, respectively (Figure 5). Similarly, in Milano the 1987-2017 mean shows a higher difference with respect to 1980-2010 for each of the months when the temperature difference ranged between 0.39 and 0.88°C, while in Bologna it ranged between –0.10 and +0.59°C (Figure S5 and S5).

The phenology from sowing to flowering for MZ, SW, WW is shown in Figure 5 for Milano and Bologna. Overall, the number of days to flowering decreased with the increase in mean air temper-

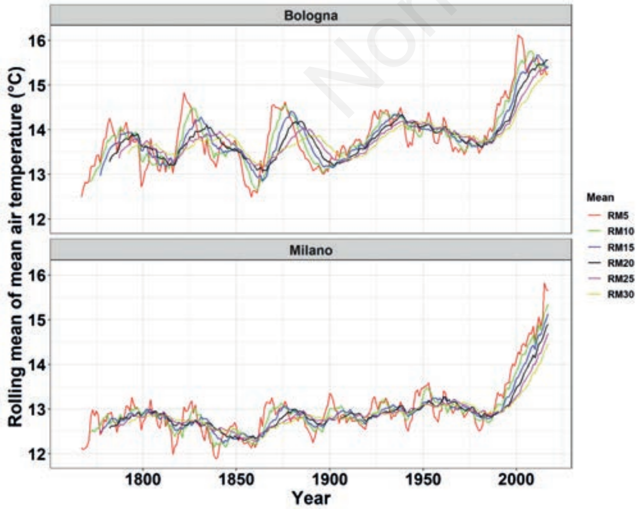

Figure 2. Rolling mean of the mean annual air temperature from 1764 to 2017 for Bologna and Milano. Each line represents a given number of n years (5, 10, 15, 20, 25, 30 years used as rolling mean values).

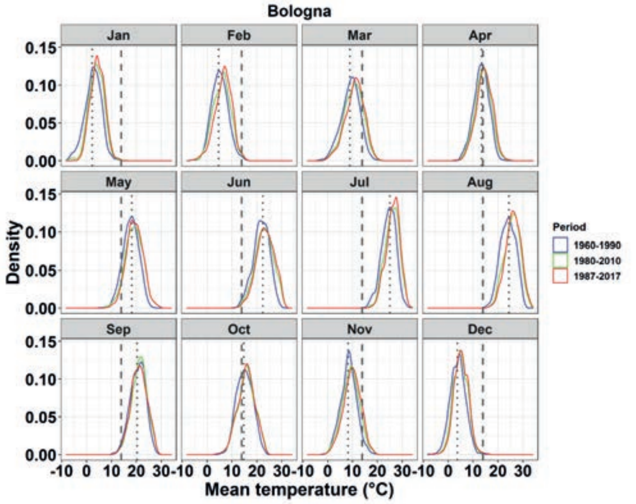

Figure 3. Density distribution of the monthly mean air temperature in Bologna for the period 1960-1990 (blue line), 1980-2010 (green line; currently used as baseline in the majority of climate change impact studies), and 1987-2017 (red-line). The vertical dashed grey line is the long-term (1764-2017) annual mean air temperature while the vertical dotted grey line is the monthly long-term (1764-2017) mean air temperature.

ature, with different patterns for each of the three cereals. For the MZ crop there is a reduction of about 5 days for each degree of mean temperature increase. The MZ phenology from sowing to flowering ranged from 88 to 33 days across the whole dataset, depending on the mean air temperature. The SW crop showed an overall reduction of 13 days to flowering with increasing air temperature, with a higher reduction in rate in Bologna than Milano (Figure 5). For WW the decreasing rate of the timing to flowering is 12 days °C^{-1}, and there was a distinction of the different years only for Bologna. But respect to SW the points of WW were more spread . For both SW and WW the number of days from sowing to flowering ranged from 220 to 150 (Figure 5).

The WW model also considers the vernalization impact and therefore Figure 6 shows the day when vernalization ends for each of the growing seasons considered in the study. The end of vernalization was defined as the day when the crop satisfies the vernalization requirements. The duration of vernalization decreased over the years for both locations, ranging from 62 to about 38 days in Milano, and from 50 to 27 days in Bologna, with a reduction of 0.12 and 0.089 days per year, respectively (Figure 6).

The time from flowering to maturity is reported in Figure 7. Overall, the grain filling period for the two locations had similar patterns for the winter and spring wheat but it was different for maize. In Bologna, maize grain filling decreased from 89 to 30 days as the mean air temperature increased from 17°C to 26°C, and the data related to the 700-800s periods showed lower mean air temperature with respect to the later periods. In Milano, the reduction in the grain filling period was similar but with a lower separation between periods. For the spring and winter wheat rate of reduction of the grain filling period was about 2 days °C^{-1}. For this particular growth stage there was not a clear distinction of earlier and later periods impacts on shortening the phenology (Figure 7).

Figure 8 shows the number of days with maximum daily air temperature (T_{max}) above 34°C for the quarters of May-June-July (MJJ) and July-August-September (JAS) for both locations. Overall, the number of T_{max}>34°C varied between 0 and a maximum of 37 days for Bologna and 29 for Milano. For both quarters (MJJ and JAS), the T_{max}>34°C were distributed across the long-term time-series with Bologna showing a uniform and high frequencies of those occurrences. Overall, in the last 40 years the number of days of T_{max}>34°C has increased with respect to the past in both locations. For example, in Bologna the number of days of T_{max}>34°C in the subsequent 30-year periods, *i.e.* 1960-1990, 1980-2010, 1987-2017, increased gradually from 143, to 499 and 750 respectively (Figure 8). Although Milano had a smaller number of days of T_{max}>34°C there was clear increase in the last 30 years; in fact, considering the same time-periods as Bologna,

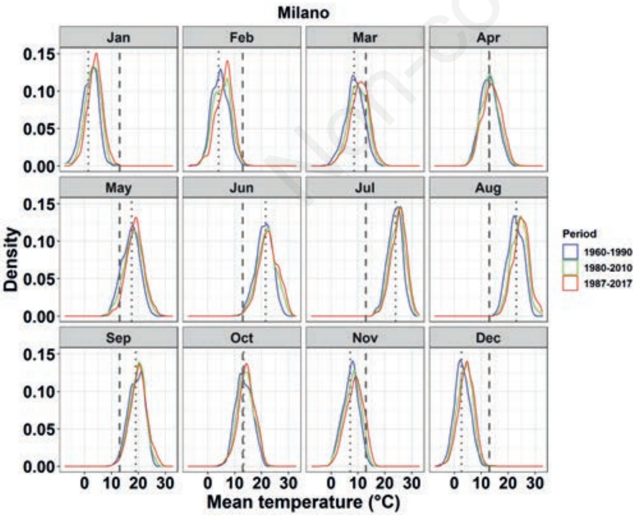

Figure 4. Density distribution of the monthly mean air temperature in Milano for the period 1960-1990 (blue line), 1980-2010 (green line; currently used as baseline in the majority of climate change impact studies), and 1987-2017 (red-line). The vertical dashed grey line is the long-term (1764-2017) annual mean air temperature while the vertical dotted grey line is the monthly long-term (1764-2017) mean air temperature.

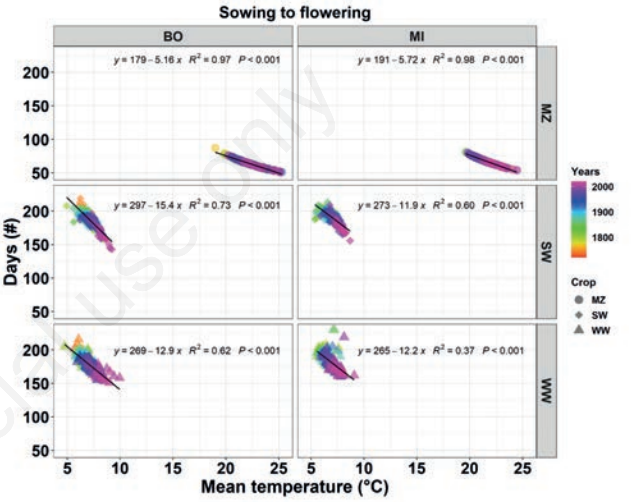

Figure 5. Relationship between the number of days from sowing to flowering in Bologna (BO) and Milano (MI) for the maize (MZ), spring wheat (SW), and winter wheat (WW) from 1764 to 2017. The continuous colour scale represents the individual year from 1764 to 2017.

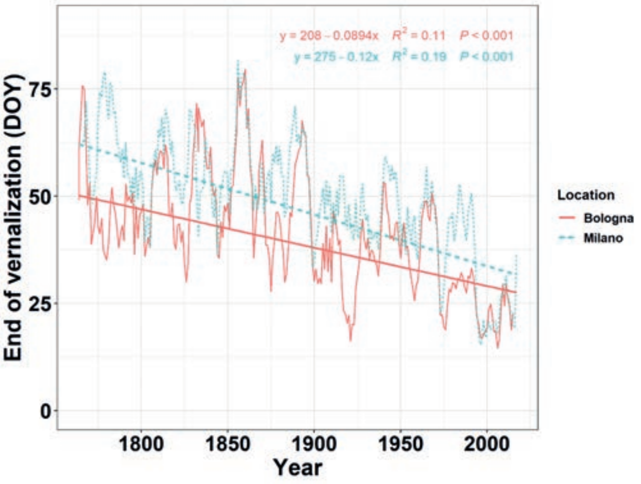

Figure 6. End of vernalization day for the Winter Wheat cultivar considered in the study in Bologna (red lines) and Milano (dotted blue lines) from 1764 to 2017.

the period 1987-2017 had 154 days of T_{max}>34°C in respect to the 1800s which had only 124 days in total (Figure 8).

The four grapevine varieties considered in this study showed distinct phenological patterns for the periods under consideration (Figures 9 and 10). In contrast to the wheat crop, some of the phenological stages of vines were dissimilar for different periods of time. Overall, there was more variability in terms of data distribution for the endodormancy, and endodormancy-bud break phases for both locations and for all the vines (Figures 9 and 10). In both locations the endo-dormancy period decreased with increasing air temperature for Cabernet-Sauvignon and Chardonnay of about 8-10 days °C^{-1}. For Glera and Merlot no clear variations in endo-dormancy with temperature can be found. The endodormancy-bud break period also showed a strong decrease over the years in both locations and for all the vines, with a rate of about 11-14 days °C^{-1}. However, the shift in phenology over the years was noticeable only in Bologna, and for Glera and Merlot (Figure 9). The period from flowering to veraison does not show a significant variation with temperature, being of about 2-4 days °C^{-1} for both locations (Figures 9 and 10).

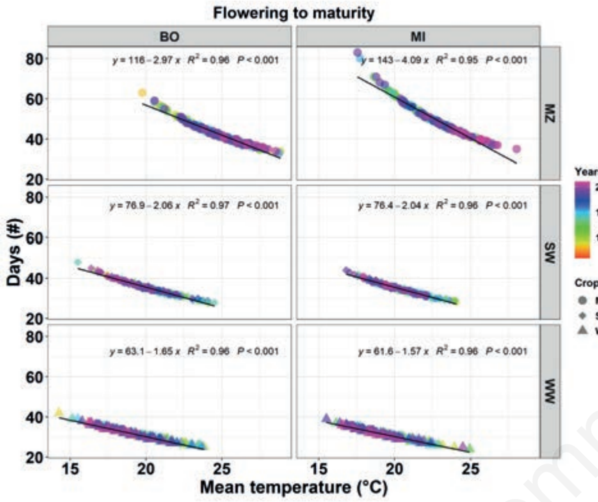

Figure 7. Relationship between the number of days from flowering to maturity in Bologna (BO) and Milano (MI) for the maize (MZ), spring wheat (SW), and winter wheat (WW) from 1764 to 2017. The continuous colour scale represents the individual years from 1764 to 2017.

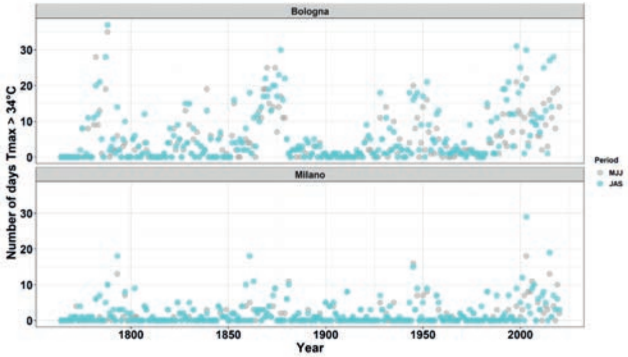

Figure 8. Number of days with maximum air temperature (T_{max}) above 34°C for Bologna and Milano (1764 to 2017) for the May-June-July period (MJJ; grey dots) and for the July-August-September (JAS; cyan dots).

Discussion

The use of long-term air temperature records (1764-2017) at two Italian sites (Milano and Bologna) have shown a shortening of phenological phases in cereals and perennial crops as air tempera-

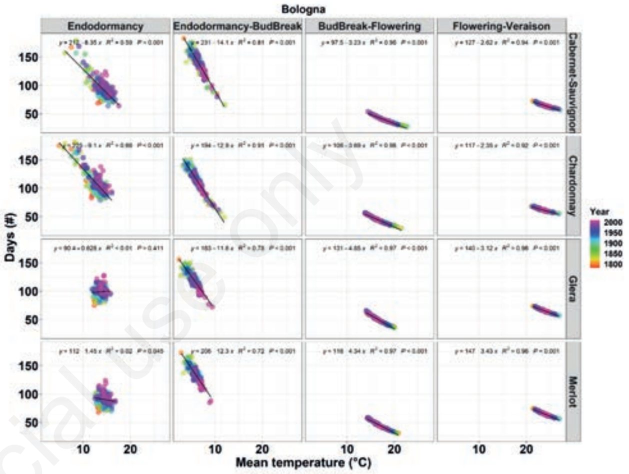

Figure 9. Relationship between mean air temperature and number of days to Endodormancy, Endodormancy to Bud Break, and Flowering to Veraison for Cabernet-Sauvignon, Chardonnay, Glera and Merlot in Bologna. The continuous colour scale represents the individual year from 1764 to 2017.

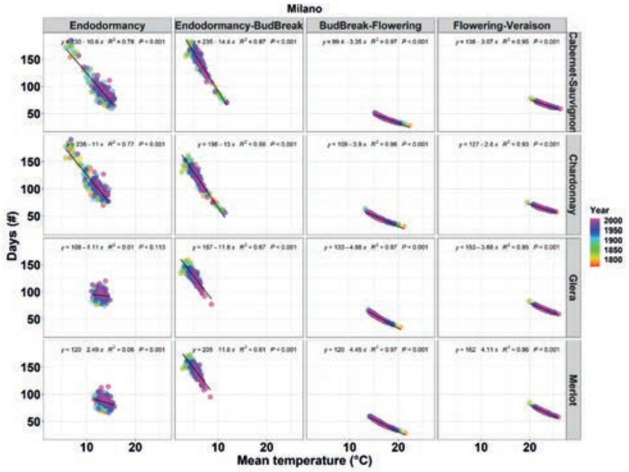

Figure 10. Relationship between mean air temperature and number of days to Endodormancy, Endodormancy to Bud Break, and Flowering to Veraison for Cabernet-Sauvignon, Chardonnay, Glera and Merlot in Milano. The continuous colour scale represents the individual year from 1764 to 2017.

ture increases, with this trend becoming more evident in recent years. In addition, in the case of WW any further increase in air temperature will cause a delay in vernalization fulfilment as explained in detail below. This will cause the grain filling phase to occur in warmer conditions with negative impacts for final yield. This is particularly evident for the growing season months for the period 1987-2017 that is warmer than periods utilized as a baseline in climate change studies (*e.g*. 1980-2010).

All long meteorological series are affected by gaps and irregular sampling in the early instrumental period, especially in the 18th century. This occurred for a number of reasons discussed elsewhere (Camuffo and Jones, 2002; Camuffo *et al.*, 2017; Camuffo *et al.*, 2019; Camuffo *et al.*, 2020; Camuffo *et al.*, 2022). The long Bologna series of temperature and precipitation have been recovered by the authors directly from the original sources and reconstructed using validated methodologies (Camuffo *et al.*, 2017; Camuffo *et al.*, 2019). As the early period of the series, from 1764 to 1814, misses the daily extremes of temperature T, in this study a methodology has been implemented to reconstruct over the calendar year the daily maximum (T_{max}) and minimum (T_{min}) values from the daily mean (T_{mean}). The data calculated with the models fit well the observed data, respecting their variance.

In this study, a simple response function to air temperature is used, similar to those used as sub-routines for more complex crop simulation models (Alderman *et al.*, 2013). In a maize simulation study, Bassu *et al.* (2014) found that in France, for 23 maize models, using the same genotype, there was an advance in flowering time of –5.5 days °C^{-1}, which was conservative across models. The results of this study (–5.3 and –5.7 days per °C for Bologna and Milano, respectively) agree with those findings.

For wheat, the temperature response functions to phenology and growth processes have been at the centre of modelling improvement efforts, because it has been found that the large uncertainty in yield simulation among 27 wheat models was due to crop response to temperature (Alderman *et al.*, 2013; Asseng *et al.*, 2013; Wang *et al.*, 2017). Wang *et al.* (2017) derived, based on recent data and scientific evidence, a new temperature response function following a common Arrhenius-type of curve with the minimum temperature of 0°C, the optimum of 27.7°C and the maximum of 40°C. They developed a set of new temperature response functions for other physiological processes and found that those new response functions improved phenology, yield and biomass simulations (Wang *et al.*, 2017). The phenology model used in this study was simpler to implement, but it produced robust and acceptable results when compared to more complex phenological models (Wang *et al.*, 2017).

It is important to point out that air temperature impacts other important physiological processes that can in turn impact yield. For example, increasing senescence rates, photosynthetic rates, leaf initiation and expansion rates, the growth of nodes and tillers, the grain abortion rates, and pathogens infections. To take those other impacts into account, crop simulation models are used (Asseng *et al.*, 2013; Asseng *et al.*, 2015) and while the approach presented here is simpler, results of showed that for wheat (spring and winter) there was a shortening of 13 days °C^{-1} of air temperature increase which is in line with the findings of Asseng *et al.* (2015) where multi crop models were used.

Winter wheat has to fulfil the vernalization requirements to reach flowering time, this means that the crop needs to accumulate a given amount of cold days before flowering. Compared to Bologna, more time is needed in Milano to reach vernalization requirements over the past centuries, because of sub-optimal temperature conditions for vernalization. The analysis of the monthly temperature patterns indicates that the distribution of the past daily temperatures from November to March (the vernalization period) was closer to the lower limit for vernalization (3°C) in Milano than in Bologna. The observed increase in temperature toward the optimal range (from 3°C to 10°C) allowed the crop to fulfil the vernalization requirement faster. With the increase in air temperature from 1980 onwards, Milano still fulfils the vernalization requirements within the optimal window, while Bologna is close to the upper limit. A further increase in air temperature will cause a shift towards supra-optimal range and therefore delays in vernalization fulfilment. In turn, this will cause the grain filling phase to occur in warmer conditions with consequences for final yield. Similar findings have been reported by Ruiz-Ramos *et al.* (2018) in a study exploring the adaptation strategies for wheat cultivation in Spain, in which the winter wheat cultivar analysed was longer adapted to warmer climates because of lower yields and crop failure due to disturbed vernalization. From flowering to maturity there was a reduction of 2 days °C^{-1} increase in temperature which was less than the 5 days °C^{-1} reported in the global study of Asseng *et al.* (2015) and 7 days °C^{-1} reported in Asseng *et al.* (2017). The time from flowering to maturity is highly dependent on the cumulative heat exposure expressed as heat sums (°Cd) and is variable among genotypes. In addition, the air temperature in the two previous studies ranged between 12 and 32°C which means that wheat was exposed to higher temperatures which generally caused a faster rate of development.

The time to maturity is also dependent on flowering date, in a sense that if flowering happens later in the growing season the grain filling period will be shifted towards a warmer period and the accumulation of the required heat sums will be fulfilled earlier. The results of this study showed a stronger response to increased temperature which caused a greater advancement of the flowering time. This caused the grain filling to occur in relatively cooler periods. In fact, the trend of decreased air temperature from flowering to maturity (Figures S6 and S7) indicates such behaviour. It is worth noting that this compensation was only evident in wheat and not maize because of the different growing cycle. This result suggests that wheat has some room for further adaptation to the projected warming climate, but this is not true for maize.

For the crops considered in this study, extreme temperature experienced during grain filling period can have a major impact on productivity (Hatfield and Prueger, 2015). Over the centuries, the frequency of extreme temperatures have increased at both locations, especially during a very important stage of the cereals, the grain filling period. The choice of maximum air temperature above 34°C as upper threshold was selected because it negatively impacts crop phenology (López-Cedrón *et al.*, 2005). In this study, the reproductive period for maize (Jul-Aug-Sep) and wheat (May-Jun-Jul) showed that in Bologna the 'peaks' of number of days with T_{max}>34°C are cyclical, but the number of points has increased over the centuries. This was more evident in Milano where there has been an increase in terms of number of days with T_{max}>34°C that were not experienced in previous periods (Figure 8).

With the exception of the endo-dormancy phase (1st September-End of endo-dormancy), the four grapevine varieties (Cabernet-Sauvignon, Chardonnay, Glera and Merlot) showed similar clear negative response of the phase duration to increasing temperature in both locations. Two different phenological behaviours among varieties can be observed for the duration of endo-dormancy, the ones of Glera and Merlot (with no significant changes) and the Cabernet-Sauvignon and Chardonnay (that showed negative trends). This different behaviour can be ascribed to the wider active chilling accumulation range for Glera and

Merlot (from –2.2°C to 7.7°C, 90% of effective chilling) compared to Cabernet-Sauvignon and Chardonnay (from 4.0°C to 6.8°C, 90% of effective chilling; Figure S2, CU). The strong response observed in Cabernet Sauvignon and Chardonnay indicates an sub-optimal thermal regime in the past (particularly in the period 1850-1900) that required more time to fulfil the chilling requirement for endo-dormancy release. Increasing temperature in later periods allowed earlier fulfilment of these requirement and a progressive reduction in the duration of the phases. This may represent a major risk under projected climate, particularly for varieties with narrow ranges of effective temperature, such as Cabernet-Sauvignon and Chardonnay. In fact, it can be speculated that future increases in air temperature may cause the chilling requirement to not be satisfied with excessive delay or failure of reaching the subsequent phases (Fila, 2012; Leolini *et al.*, 2018). In this context, a reduced chilling requirement for the same effective temperature range, as in Cabernet-Sauvignon compared to Chardonnay, may be considered an advantage in future warming environment.

The duration of the endo-dormancy phase has consequences on the eco-dormancy period (from end of endo-dormancy to budbreak). Higher late winter temperatures determine an early occurrence of budbreak, as found in all varieties. Irregular budbreak impacts on the grapevine growing cycle with negative consequences for plant vegetative growth (Dokoozlian, 1999; Lavee, 2000), fruit development and wine production (Jones and Davis, 2000; Santos *et al.*, 2020). The advancement of budbreak causes a shift of the budbreak-flowering phase in cooler periods as reported by Leolini *et al.* (2018) and Sadras and Moran (2013). This may increase the risk of late frosts or sub-optimal temperatures around flowering, affecting pollen germination, flower development and fruit-set, resulting in a limited berry size and weight at harvest (Greer and Weston, 2010).

Higher air temperature (T_{max}>35°C) during the flowering-veraison stage strongly affects berry ripening and final grape yield and quality. This can lead to a decoupling between technological and phenolic maturation and increase sugar accumulation (Soar *et al.*, 2008; Greer and Weston, 2010). To this end, the increase of the number of days with extreme temperatures (Figure 8) during May-June and July-August raise concerns about wine production and quality in future warmer climates where these conditions are expected to be exacerbated (Leolini *et al.*, 2019; Fraga, 2020).

For this reason, short-term adaptation strategies (*e.g.* pruning or selection of specific clones or rootstocks) to delay fruit maturation towards the cooler period of the growing season are currently suggested (Santos *et al.*, 2020). With this regard, the application of phenological models can be useful to improve knowledge of the impact of temperature on varieties-specific phenological developments (Chuine *et al.*, 2000b; Leolini *et al.*, 2020).

Conclusions

In conclusion, the long-term weather series highlighted how the phenology of cereal and perennial crops has been particularly affected in the last few decades. Such increases in air temperature caused a shortening of the growing season and a shift of developmental stage durations for each crop considered in this study. In addition, the number of days in which air temperature is above a given physiological threshold increased over time, and this has implications for development and senescence rates. A further increase of air temperature will cause disruption in vernalization requirements for winter wheat, negatively impacting grain yield. Agronomic short-term adaptations strategies for cereals would need to focus on optimizing the Genotype × Environment × Management through optimal choice of cultivars and changing planting dates. In vines adaptation efforts would focus on pruning strategies or (when possible) selecting newer clones or rootstocks. In this study, vine and grain quality (and yield) were not explored because of a lack of suitable soil-management-rainfall data required for deterministic crop-soil-management-environment type of crop models.

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