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Effects of inter-annual climate variability on grape harvest timing in rainfed hilly vineyards of Piedmont (NW Italy)

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Abstract. The current scenario of global warming impacts viticulture, influencing grape and wine quality. A study was carried out in the "Basso Monferrato" region, a rainfed hilly vine-growing area in NW Italy, to investigate the relationships between climate variables and grape harvest dates. The dates of harvest for some local wine grape varieties were recorded from 1962 to 2019 in the Vezzolano Experimental Farm and surrounding vineyards. Three series of climate data were investigated by means of trend analysis for temperature variables, Huglin index, and precipitation during the growing period. A significant trend was found for temperature variables (positive) and harvest dates (negative), indicating anticipation of harvest beginning from 11.6 to 34.2 days in the 58-years study period, depending on the variety. The influence of increasing temperature and Huglin index in anticipating the harvest period, particularly the harvest beginning, was also highly significant for all the considered varieties and vineyards in the Monferrato area. Implication under a climate warming scenario, the relevance of having available continuous and homogeneous datasets and possible future studies were also discussed.

Keywords: viticulture, climate change, agro meteorology, time series analysis, Italy.

1. INTRODUCTION

The *Global Warming of 1.5* °C IPCC special report (IPCC, 2018) clearly highlights and documents the numerous effects of the observed climate changes on natural and human activities. Not only an increase in temperature but a dramatic change in the frequency of extreme events, such as heatwaves, is also expected. In the last years, many studies investigated the sharp impacts of climate change on different agricultural sectors (Jones and Davis, 2000; Jones *et al.*, 2005; Jones, 2007; Moriondo and Bindi, 2007; Tomasi *et al.*, 2011; Ramos, 2017; Kociper *et al.*, 2019). Concerning viticulture, the climate effects significantly influence grape and wine quality (Mariani *et al.*, 2009). Grapevine (*Vitis vinifera L.*) growing is one of the most relevant agricultural sectors in Italy, with 708.000 ha, ranking at the third position in Europe for vineyard cultivation, after Spain and France (OIV, 2020). The Piedmont region (NW Italy) has a vineyard surface of 41.360 ha, almost totally devoted to wine production (ISTAT, 2020). In 2014 *The Vineyard Landscape of Piedmont: Langhe, Roero and Monferrato* was recognised as a UNESCO World Heritage Site for the outstanding landscapes and the importance of vine-growing and winemaking in the Region (UNESCO, 2020).

The study of climate evolution and its environmental, economic, and social effects need to be monitored through its variations over time through a historical series of meteorological data. This kind of data represents an essential resource for agro-meteorology to understand the current and predictive dynamics, address agronomical choices, and finally determine their qualitative and quantitative effects on agricultural production. The availability of long-lasting, complete and accurate data series is a fundamental added value to predict and react to climate variability. Inter-annual climate variability determines effects on the beginning and duration of phenological stages and, ultimately, on the grape harvest and yield (Jones and Davis, 2000). Grapevines have four primary developmental stages: (i) budbreak, (ii) flowering, (iii) veraison (beginning of maturation) and (iv) full ripeness (harvest). The time between these stages varies greatly with grape variety (Tomasi *et al.*, 2011), and it is mainly influenced by the air temperature of the growth period (Mullins *et al.*, 1992). Previous studies (Jones *et al.*, 2005; Ramos *et al.*, 2008) reported changes of 5-10 days for these stages per 1 °C of warming over the last 30–50 years averaged over several wine regions and varieties. In addition, the observed increase of warm days poses a threat to grape quality because it causes a situation of imbalance at maturity, concerning sugar content, acidity and phenolic and aromatic ripeness (Camps and Ramos, 2012).

Climate change brings warmer conditions, generally associated with shorter intervals between phenological stages and earlier harvest occurrence (Tomasi *et al.*, 2011). The grape harvest timing is closely related to the aptitude of the vine to yield and ripen fruit to the optimum levels (Jones and Davis, 2000). In the Italian region of Veneto (NE Italy), grape maturity dates have trended 19 days earlier over 45 years (1964–2009) for several varieties (Tomasi *et al.*, 2011), and similar trends for the harvest dates were observed across numerous other locations in Europe (Jones *et al.*, 2005) for many wine grape varieties. In the Spanish region of Penedès, an analysis of temperature and precipitation trends was correlated with the beginning and ending dates of grape harvest: the ripeness timing showed a continuous advance of between -0.7 and -1.1 days/year (Camps and Ramos, 2012). To our knowledge, no studies have been published correlating long-time climate and harvest data series in Piedmont region. It should be useful for examine the relationships between climate variables and the responses of grapevine in a context of climate change, with particular reference to the beginning and ending harvest dates.

The purpose of this work carried out in the Basso Monferrato, a rainfed hilly wine-growing area in Piedmont, is to investigate: (i) the existence of trends within long-time climate data series, considering the vine growing season, (ii) the existence of trends within harvest dates for some local wine grape varieties and (iii) the relationships between the considered climate variables and harvest parameters.

2. EXPERIMENTS

2.1. The study area

Since 1962, the Institute for Agricultural and Earthmoving Machines (IMAMOTER) of the Italian National Research Council (CNR) has been carrying out many studies about the environmental and agronomic management of sloping vineyards in the Monferrato area, particularly in the Vezzolano Experimental Farm (45°08'N, 7°96'E, 426 m a.s.l., located in the municipality of Albugnano and managed by IMAMOTER). The results presented in this paper originated from the agrometeorological monitoring activity and the information concerning the grape harvest in the Experimental Farm and the surrounding area over the period 1962-2019. Since October 2020, IMAMOTER has become part of the new Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS).

The Vezzolano Experimental Farm is located in the northern part of the Monferrato area, namely in the "Basso Monferrato". It is extended on 27 hectares including many vineyards, mainly cultivated with Malvasia di Castelnuovo Don Bosco, Freisa and Barbera varieties. The climate is scharacterised by warm and relatively dry summer, rainy spring and autumn, and cold winter with snowfall events, corresponding to a transitional climate between pre-alpine and sublitoranean (ARPA, 2020). According to on-site meteorological data recorded in 1962-2019, the mean annual precipitation was 846 mm, mainly concentrated in May (109 mm), while the driest month was Janu-

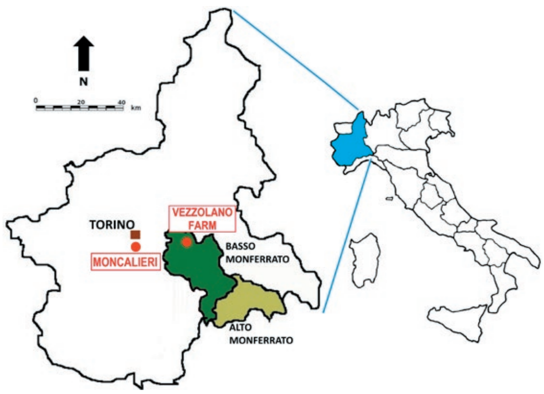

Fig. 1. Localization of the study site in Italy.

ary (43 mm). In the same period, the mean annual air temperature was 11.8 °C. The soil texture is silt loam (24% clay), and the soil is classified as *Typic Udorthent* (Soil Survey Staff, 2010; Nigrelli, 1998), derived from Miocene silty marls of the Tertiary Piedmontese Basin (Piana *et al.*, 2017). As typical in the Monferrato area, vineyards are arranged mainly with rows along contour lines ("girapoggio") or up-and-down the slope ("rittochino").

The Basso Monferrato has a long tradition of wine production, mainly dedicated to red wines, under the "Freisa d'Asti" DOC, the "Malvasia di Castelnuovo Don Bosco" DOC and the "Albugnano" DOC (Denomination of Controlled Origin) and the "Barbera d'Asti" DOCG (Denomination of Controlled and Guaranteed Origin), the highest designation of quality among Italian wines. The main grape varieties used for this purpose and cultivated in the area are Malvasia di Castelnuovo Don Bosco, Freisa, Bonarda, Barbera and Nebbiolo. The "Cantina Sociale del Freisa", a cooperative winery founded in 1953, is located in Castelnuovo Don Bosco village. In 1997 it was merged with the historic Wine Cellar of Barbera of San Damiano d'Asti in the "Cantina Sociale del Freisa - Terre dei Santi" winery, currently producing typical local wines from approximately 400 hectares of vineyards. Table 1 reports the cultivation surfaces and the yield related to "Cantina Sociale del Freisa – Terre dei Santi" in the two last years.

2.2. Climate data

In the present study, two long-lasting meteorological datasets related to Vezzolano site and to Moncalieri (near Torino) are considered to analyse inter-annual climatic variability.

The Vezzolano weather station is located in front of the farmhouse of Experimental Farm. The first station, operating since 1961 (Figure 2a) was composed by a mechanical thermo-hygrograph (Salmoiraghi, 1750 series), a pluviograph (SIAP Bologna), a totalising anemometer for wind run measuring (from 1971) and an evaporigraph, in addition to a solarimeter with graphic recorder (from 1981). The instruments were positioned in a wooden meteorological screen, about 1.3 m high from the concrete base. The devices were periodically calibrated, recording all the interventions and failures on monthly summaries of daily data. This station operated until 2006. The daily data (minimum, maximum and average temperature, average relative humidity and rainfall) were noted on the monthly meteorological agendas, indicating average and total decadal and monthly values.

Since March 2002, an automatic station was placed few meters apart from the mechanical one. It is equipped with sensors for measuring precipitation, temperature, relative humidity on an hourly basis and remote transmission systems of the data collected (Figure 2b). The station is part of the Piedmont Regional Agrometeorological Network (RAM), and its data are collected and made available to the public by the dedicated service of the Piedmont Region (Regione Piemonte, 2020).

In addition to the local data, the continuous datasets from the Moncalieri meteorological observatory are considered in this study. Long-term meteorological observations in Moncalieri – Collegio Carlo Alberto (Torino, 44°59'N, 7°41'E, 267 m a.s.l.) began in 1865 on the initiative of the Barnabite Catholic Priest and scientist Francesco Denza (Cat Berro *et al.*, 2015). The station is located within an urban area (Figure 3), atop of a historic building, as used in late 19th century, and the position of the instruments – even different from modern international

Table 1. Annual production of the "Cantina Sociale del Freisa – Terre dei Santi". For each cultivated grape varieties, total surfaces (ha) and total yield in grapes (t) are reported.

Year	Freisa		Malvasia di C. Don Bosco		Barbera		Bonarda		Nebbiolo	
	[ha]	[t]	[ha]	[t]	[ha]	[t]	[ha]	[t]	[ha]	[t]
2018	189	1453	47	400	45	316	17	123	17	125
2019	182	1060	46	275	42	222	18	67	17	98

Figure 2. Weather stations at the Vezzolano Experimental Farm: (a) the mechanical station that operated in the period 1961-2005 and, on the background, the Vezzolano Abbey (photo IMAMOTER, 11.03.2009) and (b) the automatic station placed near the older one in 2002 by the Regional Agrometeorological Network (RAM). Stations are placed in the in front of the farmhouse (photo IMAMOTER, 10.05.2008).

criteria – never changed to maintain the homogeneity of the time series. Since December 2001, an automatic weather station guarantees the continuity of measurements: temperature and relative humidity (in the Stevenson screen, as in the past), air pressure, precipitations, global solar radiation, wind speed and direction. Currently, Società Meteorologica Italiana (SMI) manages the station, collects and studies the recorded data. Data quality is regularly checked in collaboration with the leading Italian metrological institute (INRiM, Torino) within the framework of "MeteoMet" European project (https://www.meteomet.org/): instruments calibrations were carried out in 2012, 2016 and a new campaign is scheduled in 2021 (Bertiglia *et al.*, 2015). In 2018, World Meteorological Organization recognised Moncalieri observatory as "Centennial Observing Station" (WMO, 2020). The Moncalieri station is 23 km far from the Vezzolano Experimental Farm, but its series represent one of the most long-time, validated and homogeneous datasets in Piedmont and it can be considered as a reference for the surrounding area.

Figure 3. The tower of meteorological observatory in Moncalieri, managed by SMI (photo SMI, 11.04.2016).

Minimum and maximum daily temperature, and daily precipitation (Table 2) from the weather stations from the two locations (Vezzolano and Moncalieri) were used. For each year, from 1962 to 2019, temperature and precipitation variables were ssummarised for the growing season, considering three different time periods: from January to September (TMin_JS, TMax_JS, Prec_JS), from March to September (TMin_MS, TMax_MS, Prec_MS), and from April to September (TMin_AS, TMax_AS, Prec_MS). Consequently, the Huglin index was calculated for the same three periods (Hug_JS; Hug_MS, Hug_AS). According to results from previous studies carried out by Spanna and Lovisetto (2000) and by Lisa and Spanna (2003) in the Vezzolano Farm, in Piedmont vine areas when the Huglin bioclimatic heat index is calculated, as usual from April 1, it results in underestimation the real useful thermal contribution for the vine phenological development. Indeed, in March, but often already in February, many degree days useful for the phenological growth of the vine can be accumu-

Table 2. Weather stations considered in the study.

Station	Location	Altitude	timeline
Vezzolano (mechanical)	45°08'N, 7°96'E	426 m a.s.l.	1962÷2004
Vezzolano RAM	45°08'N, 7°96'E	426 m a.s.l.	2003÷2019
Moncalieri	44°59'N, 7°41'E	267 m a.s.l.	1960÷2019

lated, especially for the early varieties. Hence the choice to consider the January-September (JS) and March-September (MS) periods for the calculation of the Index. However, the calculation for the April-September (AS) period was also tested.

2.3. Grape harvest data

The data related to grape harvest timing were collected from the Vezzolano Experimental Farm of CNR-STEMS (former CNR-IMAMOTER), and from the "Cantina Sociale del Freisa – Terre dei Santi" on vineyards affiliated to the cellar in the surrounding area of the location of the weather station. The records of the harvest beginning data related to Vezzolano's vineyards cover the period from 1961 to 2019 for the Malvasia (BH_MAV), Freisa and Barbera (BH_FBV) varieties. The last two varieties are considered together as their harvest period usually is the same. The database of the "Cantina Sociale del Freisa – Terre dei Santi" of Castelnuovo Don Bosco covers the period 1958 to 2019 for the local varieties, with indication also of both the starting (BH_TS) and the ending day (EH_TS) of harvest operations.

2.4. Trend analysis

Trend analyses of the different climate variables (Tmin, Tmax, Prec, Hug for the three periods, January-September, March-September and April-September) and harvest parameters (beginning and end dates) were carried out. Trend analysis was implemented by linear regression when all conditions for parametric analysis were satisfied; otherwise, the non-parametric Mann-Kendall test (Kendall, 1975) and Sen's slope test (Sen, 1968) were carried out to determine the significance and slope of the trend, respectively. The time series were assessed for auto-correlation using the Durbin-Watson statistic. When the time series had autocorrelation, the modified Mann-Kendall test using prewhitening technique according to Hamed (2009) was applied. The interactions between climate and harvest parameter trends were also analysed. Linear regression between climate variables and harvest dates (beginning and end) was applied to identify the relationships between the different variables. Generalised least squares method was used in autocorrelation, and Kendall-Theil-Sen non-parametric regression was used when conditions for parametric linear regression were not satisfied. Statistical analyses were computed using R (R Core Team, 2020).

3. RESULTS

3.1. Characteristics and trends for climate and harvest dates of the study area

The mean values of the analysed climate variables for each considered growing period and any historical climate series, and mean values for the harvest dates are reported in Table 3. For the Vezzolano series, mean values of minimum temperature ranged from 8.5 °C to 12.6 °C and from 9.6 °C to 13.9 °C for the 1962-2004 and 2003-2019 periods, respectively, varying according to the considered growing period. The maximum temperature ranged from 18.2 °C to 22.8 °C and from 20.3 °C to 25.5 °C, for the first and second period of observation at Vezzolano, respectively. Observations at Moncalieri station across the 1960-2019 period revealed the minimum and maximum average temperature varying from 10.5 °C to 14.8 °C and 20.7 °C to 26.1 °C, respectively. The mean amount of precipitation, which showed high inter-annual variability, ranged from 402.2 mm to 656.9 mm across the three series while the Huglin index ranged from 1917.0 to 2590.2 degree-days per year. As expected, for those variables related to temperature, the mean values including in the computation the months of January and February (usually the coldest months in Italy's climate) resulted in being lower on average, 3.5 °C difference among minimum temperatures and 4.2 °C difference among maximum temperatures. Inversely, precipitation resulted lower when January and February were not computed (average difference of 115 mm).

For the Vezzolano site, mean values of minimum and maximum temperatures for the 2003-2019 series were about 1-2.5 °C higher than those recorded in the 1962-2004 series; this also resulted in more than 400 degree-days difference for Huglin index. Compared to the Vezzolano stations, Moncalieri station recorded higher temperatures (averagely 1.7 °C higher) and lower precipitations (averagely 108 mm lower).

Concerning the mean harvest dates, they differ from each other being referred to different grape varieties. Mean harvest beginning dates (BH) range between the 19th of September and the 2nd of October, while the mean ending date of harvest (EH) is the 15th of October. On average, the recorded dates vary across years in a range between 7 and 12 days.

Table 3. Mean annual values (±standard deviation) of each climate variable for the three data series and for each harvest variable.

	Variables[1]	Vezzolano 1962-2004	Vezzolano 2003-2019	Moncalieri 1960-2019
Climate	Tmin_JS (°C)	8.5 ±0.8	9.6 ±0.5	10.5 ±0.7
	Tmax_JS (°C)	18.2 ±1.1	20.3 ±0.8	20.7 ±1.3
	Prec_JS (mm)	640.3 ±198.5	656.9 ±163.6	517.8 ±156.3
	Hug_JS (°C-days)	1977.6 ±195.9	2417.1 ±146.4	2590.2 ±259.4
	Tmin_MS (°C)	11.1 ±0.8	12.4 ±0.5	13.4 ±0.7
	Tmax_MS (°C)	21.3 ±1.1	23.6 ±0.8	24.5 ±1.4
	Prec_MS (mm)	549.3 ±176.8	559.4 ±134.4	448.4 ±133.3
	Hug_MS (°C-days)	1967.6 ±193.4	2394.8 ±143.6	2577.4 ±252.0
	Tmin_AS (°C)	12.6 ±0.8	13.9±0.6	14.8 ±0.8
	Tmax_AS (°C)	22.8 ±1.2	25.5±0.8	26.1 ±1.4
	Prec_AS (mm)	489.5 ±180.8	489.4±108.9	402.2 ±124.5
	Hug_AS (°C-days)	1917.0 ±187.7	2310.0±132.3	2485.0 ±228.1
Harvest 1961-2019	BH_MAV (date±days)		27 September ±10 days	
	BH_FBV (date±days)		2 October ±7 days	
	BH_TS (date±days)		19 September ±12 days	
	EH_TS (date±days)		15 October ±8 days	

[1]Tmin_JS: mean annual minimum temperature from January to September (°C); Tmax_JS: mean annual maximum temperature from January to September (°C); Prec_JS: mean annual total precipitation from January to September (mm) Hug_JS: mean annual total value of Huglin's Heliothermal Index from January to September (°C-days). The suffix "MS" and "AS" indicate the same variables measured from March to September and from April to September. BH_MAV: mean harvest beginning date (date±days) for Malvasia (MAV); for Freisa-Barbera (FBV); for the "Cantina Sociale del Freisa – Terre dei Santi" (TS); EH_TS: mean harvest ending date (date±days) from the "Cantina Sociale del Freisa – Terre dei Santi".

The trends of historical time series were sanalysed to evaluate how climate variables have been changing within the last decades (Table 4). In general, results show significantly increasing trends with regard to temperature variables, namely minimum and maximum temperatures and Huglin index, especially for Moncalieri's series. Precipitation showed a relevant inter-annual variability, and no significant trends were observed for associated variables (Prec_JS, Prec_MS, Prec_AS) in any datasets.

In detail, concerning Vezzolano's 1962-2004 series, for all the considered periods of growing season (January to September, March to September and April to September) the Huglin index significantly increased over the period, ranging between 3.94 degree-days per year considering AS growing season and 4.96 degree-days per year when the month of March was computed in the growing season. In addition, for the MS growing season, a significant trend of 0.03 °C per year was also observed for minimum and maximum temperatures.

In Moncalieri's series, the positive trend identified for Tmin and Tmax was the same considering average values from January to September, from March to September and from April to September, showing a significant increase of 0.03 °C and 0.06 °C per year respectively. For the Huglin index the increasing trend observed in Moncalieri's series was particularly relevant. This variable demonstrated the higher significant average increase of 11.71 degree-days per year when computed from January to September.

For the Vezzolano series recorded from 2003 to 2019, only minimum temperature showed a significant increase of 0.04 °C per year.

The trends of the harvest dates (Table 5) were statistically significant for all the considered variables. They resulted in general anticipation for the beginning and the end of the harvest period. In particular, the maximum and the minimum change ratios were respectively -0.59 and -0.18 days per year, corresponding to the trends of the starting (BH_TS) and the ending (EH_TS) dates from the "Cantina Sociale del Freisa – Terre dei Santi" of Castelnuovo Don Bosco. Referring to a single variety and only to the Vezzolano farm, the starting date of harvest was anticipated by 3.7 and 2 days in ten years for Malvasia and Freisa-Barbera varieties, respectively.

3.2. Relationships between climate variability and grape harvest

The advance in the beginning and end of the harvest period was analysed in relation to different climatic vari-

Table 4. Temperature, precipitation and Huglin index trends for the three data series, significant at 95% level or higher (+ ≤ 0.050; * ≤ 0.010; ** ≤ 0.001; *** ≤ 0.0001). Numbers in brackets indicate values of R^2 or Kendall τ.

Variables[1]	Vezzolano 1962-2004	Vezzolano 2003-2019	Moncalieri 1960-2019
Tmin_JS (°C/year)	NS	0.04+ (0.21)	0.03*** (0.54)
Tmax_JS (°C/year)	0.03+ (0.09)	NS	0.06*** (0.62)
Prec_JS (mm/year)	NS	NS	NS
Hug_JS (°C-days/year)	4.43+ (0.08)	NS	11.71*** (0.62)
Tmin_MS (°C/year)	0.03** (0.15)	NS	0.03*** (0.60)
Tmax_MS (°C/year)	0.03+ (0.22)	NS	0.06*** (0.61)
Prec_MS (mm/year)	NS	NS	NS
Hug_MS (°C-days/year)	4.96* (0.10)	NS	11.39*** (0.63)
Tmin_AS (°C/year)	NS	NS	0.03*** (0.58)
Tmax_AS (°C/year)	NS	NS	0.06*** (0.56)
Prec_AS (mm/year)	NS	NS	NS
Hug_AS (°C-days/year)	3.94+ (0.19)	NS	9.97*** (0.58)

[1]Tmin_JS: mean variation per year of mean minimum temperature from January to September (°C/year); Tmax_JS: mean variation per year of mean maximum temperature from January to September (°C/year); Prec_JS: mean variation per year of total precipitation from January to September (mm/year) Hug_JS: mean variation per year of total value of Huglin's Heliothermal Index from January to September (°C-days/year). The suffix "MS" and "AS" indicate the same variables measured from March to September and from April to September.

Table 5. Harvest dates trends, significant at 95% level or higher (+ ≤ 0.050; * ≤ 0.010; ** ≤ 0.001; *** ≤ 0.0001).

Variables[1]	N	Slope
BH_MAV (days/year)	59	-0.37***
BH_FBV (days/year)	46	-0.20***
BH_TS (days/year)	59	-0.59***
EH_TS (days/year)	59	-0.18*

[1]BH_MAV: mean variation per year of harvest beginning date for Malvasia (days/year); BH_FBV: mean variation per year of harvest beginning date for Freisa-Barbera (days/year); BH_TS: mean variation per year of harvest beginning date from the "Cantina Sociale del Freisa – Terre dei Santi" (days/year); EH_TS: : mean variation per year of harvest ending date from the "Cantina Sociale del Freisa – Terre dei Santi" (days/year); N: number of years in each dataset.

ables that had shown significant trends. Almost all performed regression analysis resulted significant (P<0.05) or highly significant (P<0.0001). Table 6 reports the change ratios obtained in the regression analysis, estimating the average change in days of the harvest dates, in relation to temperature variables. In most of the sanalysed cases, the harvest date exhibited a negative correlation with the average minimum and maximum growing season temperature (Tmin_JS, Tmax_JS, Tmin_MS, Tmax_MS, Tmin_AS, Tmax_AS). According to the harvest date variables, all results for temperature variables showed significant variability in the absolute values of the change ratios, the considered growing season and the considered series. Concerning minimum temperatures, the starting date of harvest was anticipated from 5.32 days/°C for (BH_MAV for Tmin_MS) to 13.01 days/°C (BH_TS for Tmin_JS). Whereas, with regard to maximum temperatures, the starting date of harvest was anticipated from 1.62 days/°C for (BH_TS for Tmax_JS) to 7.46 days/°C (BH_TS for Tmax_MS). The change ratios for the minimum temperature for all the three series resulted in the highest (in absolute terms) with a very high significance level. For the average maximum temperature recorded at the Moncalieri observatory, the change ratios were similar considering January or March as starting month, ranging from -4.18 days/°C and -4.20 days/°C to -7.25 days/°C and -7.46 days/°C for the final (EH_TS) and starting (BH_TS) dates of harvest, respectively, for farms associated to the "Cantina Sociale del Freisa – Terre dei Santi" of Castelnuovo Don Bosco. The same values for AS period resulted slightly lower (about 1 °C).

A significant correlation was always found between the Huglin index and the harvest dates, in all cases with negative values ranging from -0.02 days/°C- days to -0.04 days/°C-days. Absolute values of the change ratios for the Huglin index were very similar among the three considered growing seasons.

4. DISCUSSION

Mean annual values of minimum and maximum temperature were lower for the Vezzolano long-term

Table 6. Relationship between harvest dates and climatic variables[1], significant at 95% level or higher (+ ≤ 0.050; * ≤ 0.010; ** ≤ 0.001; *** ≤ 0.0001).

Climate series	Independent Variable[1]	Change ratio			
		BH_MAV	BH_FBV	BH_TS	EH_TS
Vezzolano 1962-2004	Tmax_JS (days/°C)	-6.59***	-4.59***	-1.62***	-3.05**
	Hug_JS (days/°C-days)	-0.02***	-0.03***	-0.02***	-0.02***
	TMin_MS (days/°C)	-5.32***	-5.33**	-6.22***	-3.60**
	Tmax_MS (days/°C)	-6.62***	-4.69***	-2.45***	-3.46***
	Hug_MS (days/°C-days)	-0.03***	-0.03***	-0.02***	-0.02***
	Hug_AS (days/°C-days)	-0.02***	-0.03***	-0.02***	-0.02***
Vezzolano RAM 2003-2019	Tmin_JS (days/°C)	-11.80*	NS	-13.01***	-11.93**
Moncalieri 1961-2019	Tmin_JS (days/°C)	-9.35***	-6.89***	-6.50***	-6.19***
	Tmax_JS (days/°C)	-5.98***	-4.54***	-7.25***	-4.18***
	Hug_JS (days/°C-days)	-0.03***	-0.02***	-0.04***	-0.02***
	Tmin_MS (°C/year)	-9.18***	-6.90***	-11.48***	-6.80***
	Tmax_MS (°C/year)	-5.60***	-4.26***	-7.46***	-4.20***
	Hug_MS (days/°C-days)	-0.03***	-0.02***	-0.04***	-0.02***
	Tmin_AS (days/°C)	-8.36***	-6.20***	-11.31***	-5.68***
	Tmax_AS (days/°C)	-5.14***	-3.97***	-6.79***	-3.83***
	Hug_AS (days/°C-days)	-0.03***	-0.02***	-0.04***	-0.02***

[1] Tmin_JS: mean change ratio of harvest dates for each °C variation of minimum temperature from January to September (days/°C); Tmax_JS: mean change ratio of harvest dates for each °C variation of maximum temperature from January to September (days/°C); Hug_JS: mean change ratio of harvest dates for each °C-day variation of total value of Huglin's Heliothermal Index from January to September (°C-days). The suffix "MS" and "AS" indicate the same variables measured from March to September and from April to September. BH_MAV: mean variation per year of harvest beginning date in relation to temperature variables for Malvasia (MAV); for Freisa-Barbera (FBV); for the "Cantina Sociale del Freisa – Terre dei Santi" (TS); EH_TS: mean variation per year of harvest ending date in relation to temperature variables for the "Cantina Sociale del Freisa – Terre dei Santi".

(1962-2004) series than for the 2003-2019 period. Differences in average temperature can be partially ascribed to different sensors technology implemented in the RAM weather station. Nevertheless, the average annual temperature in Piedmont in the period 2000-2015 was higher than the reference 30-years (1971-2000) average temperature (ARPA, 2020); thus the most recent series likely reflects, to some extent, an increase of local temperature. Average temperatures measured at the Moncalieri observatory were the highest. The station's location at a lower altitude and in an urban context positively influences the measured temperature, especially maximum values in summer. The differences in measured temperatures are also reflected in the average values of the Huglin index. Mean precipitation was very similar for the two Vezzolano series. It was the lowest at Moncalieri station, due both to topographic reasons and to the station setup, with rain gauge placed at 26 meters from soil surface, likely resulting in underestimation of the precipitation amount due to the higher wind speed (Pollock *et al.*, 2018). The Vezzolano and Moncalieri series cover 42 and 59 years of weather observations, respectively, that were recorded homogeneously, and thus allow us to study relationships between climate data and harvest information collected over the same period. The analysis of the same relationships through a shorter and more recent series (Vezzolano 2003-2019), which corresponds to most of the datasets available in the region, highlighted the relevance of having available continuous and homogeneous datasets to carry out studies about the impact of climate temporal variability on crop growth and development.

The increase in mean maximum temperature (Tmax_JS and Tmax_MS) observed at Moncalieri over the whole period (1960-2019) is twice that of the trend obtained for the Vezzolano long-time series. This is particularly noteworthy since the difference between the two positive trends can be attributed to the inclusion in the Moncalieri series of the most recent 15 years, considering that in Piedmont the increasing trend of daily maximum temperature in the period 1981-2015 was 0.062 °C/year, while in the period 1958-2015 the observed trend was 0.038 °C/year (ARPA, 2020). This result is also in agreement with the last IPCC assessment report (IPCC, 2014), highlighting that each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The increasing trend detected in the average temperature at the rural weather station of Vezzolano was not affected by urbanisation, thus can be ascribable entirely to the global warming trend.

The observed increasing trend of the Huglin index in the two long-term series (Vezzolano 1962-2004 and Moncalieri 1961-2019) was consistent with the temperatures increase. The relative mean annual values were generally in line with those observed in other Mediterranean viticultural areas. Indeed, in the Veneto region of Italy, the Huglin index for the 1964-2009 period averaged 2457 (Tomasi *et al.*, 2011), while in the Ribera del Duero area of Spain, for the period 2003-2013, a mean yearly Huglin index ranged from 1973 to 2328, varying according to the different considered sites (Ramos *et al.*, 2016). In addition, in their study, Ramos *et al.* (2016) observed a positive correlation of the Huglin index with sugar content and, at the same time, a negative correlation with the colour index and acidity levels, meaning the higher the Huglin index, the higher the maturity level of the grapes. In the present study two aspects resulted particularly relevant concerning the obtained values of Huglin index and associated classes of viticultural climate as defined by Tonietto and Carbonneau (2004). Firstly, differences among the three considered growing periods January-September, March-September and April -September were very marginal; therefore, the findings by Jones *et al.* (2010) supporting that, in a context of generally warmer temperatures, considering longer time span of growing season did not produce any meaningful differences in terms of viticultural climate classification were confirmed. Nevertheless, the trend of the Huglin index over a long-term period of observation showed a higher increase, from 12% to 26%, including March (+26% and +14%) or even February and January (+12% and +17%) in computation than the baseline method considering April-September, respectively at Vezzolano and Moncalieri. In particular, for the Vezzolano 1962-2004 series, the trends of the Huglin index for a larger time span of growing season indicate the contribution of late winter and early spring months in bringing forward conditions for vine's development.

Secondly, considering the site of Vezzolano, in 1962-2004 series, the Huglin index ranged 1917.0-1977.6 falling in the "temperate" class (1800 < HI < 2100), while 2003-2019 series the index ranged 2310.0-2417.1, falling in "warm-temperate" (2100 < HI < 2400) and "warm" (2400 < HI < 3000) class. The same situation was observed in a previous study (Laget *et al.*, 2008) carried out in the last decades in France where in some zones of the Hérault département, the Huglin index evolved with the result that some viticultural zones classified as "warm-temperate" between 1975 and 1996 were re-classified as "warm" between 1997 and 2005. As supported by some authors (Ramos *et al.*, 2016; earlier occurrences of phases and shorter phase duration in the future. The impact varies depending on the geo-localization of the studied region and its microclimate. The objective of this study is to further understand the impact of climate change on grapevine phenology by studying the role of varieties and microclimates through a regional assessment carried out in two future periods of time (2021–2050 and 2071–2099)(Alikadic *et al.*, 2019), the Huglin bioclimatic index is particularly interesting to follow in later season events, between veraison and harvest, being able to highlight ripening potentials of grapes. For this reason, future studies could investigate how the Huglin index evolve along with the growing stages of the vine in the study area and to what extent it can explain variation in the main phenological events under a climate warming scenario.

In the Vezzolano Experimental Farm the mean beginning harvest date varied according to grape variety (from 27 September to 2 October). The harvest beginning of farms affiliated to the "Cantina Sociale del Freisa – Terre dei Santi" was anticipated by at least 8 days, with greater inter-annual variability. The relevant variability of the beginning harvest dates, that ranged from 14 to 24 days was explained by the clear identification of a significant decreasing trend in all cases, from 11.6 to 34.22 days in 58 years (1961-2019), for harvesting Freisa-Barbera at Vezzolano and different varieties from vineyards affiliated to the "Cantina Sociale del Freisa – Terre dei Santi", respectively. Similar studies in other European countries led to comparable results, moving from the Mediterranean region towards more continental areas. In Spain, Camps and Ramos (2012) identified an advance of about 12 days, on average, as date of the beginning of harvest over the last 14 years of their study in the Penedès region. Studies in France reported advancing of the harvest between 18 and 21 days in the period from 1940 and 2000 (Ganichot, 2002) or by 2 weeks between 1972 and 2002 (Duchêne and Schneider, 2005). In Italy, Tomasi *et al.* (2011) detected that the beginning harvest dates were 19 days earlier over 1964–2009 for several varieties in Veneto. In eastern Austria, Koch *et al.* (2009) also showed a trend towards earlier harvest times between 1970–2007 with a 5-days advance every 10 years in Klosterneuburg, and an approximate

3-days advance every 10 years in the Vienna vineyard area. The anticipation of the harvest date in the long-term period could be affected by several factors, not only to climate-related ones, such as changes in the method for assessing the fruit ripening, or vineyard management. Nevertheless, the trend for harvest dates detected for the Monferrato areas appears comparable to evident trends already identified over different European regions and varieties. In addition, similar trends have been seen for other phenological phases by studies based on long-time climate series and also considering projections obtained from modelling. In Piedmont, long-term simulations performed over 60 years (1950-2009) with a crop growth model for Nebbiolo variety showed statistically significant variations of most of the model output variables (phenological stages, berry sugar content, LAI Maximum value, yield), with larger time trend slopes referring to the most recent 30-year period (1980–2009), thus confirming that ongoing climate change started influencing local vineyards since 1980 (Andreoli *et al.*, 2019). Based on crop model simulations over Europe for the period 2041-2070, Fraga *et al.* (2017) observed that mean phenological timings are projected to undergo significant advancements (e.g. budburst/harvest can be >1 month earlier), with implications also in the corresponding phenophase intervals.

The influence of inter-annual changes in temperature in anticipating the harvest period, particularly the harvest beginning, was significant for all the considered varieties and vineyards, in relation to the average temperature of the three series. The highest change ratios (absolute values) have been obtained for the 2003-2019 Vezzolano RAM series. The increase of the Huglin index showed a highly significant influence in determining anticipation of harvest, regardless of the considered growing season. Nevertheless, the significant trends identified for the Monferrato area confirm that temperature is the primary driver of grapevine phenology (Alikadic *et al.*, 2019), especially for harvest. Several studies show that the temperature rise is highly correlated to the earlier occurrence of phenological phases, affecting the final quality of products (Jones and Davis, 2000; Jones *et al.*, 2005; Dalla Marta *et al.*, 2010; Bock *et al.*, 2011). The timing of maturity directly relates to wine quality, since grape composition and subsequent wine quality are linked to growing season temperatures (Jones *et al.*, 2005; Jarvis *et al.*, 2017). Leolini *et al.* (2019), modelling the performance of Sangiovese grape variety in Tuscany, observed that a progressive increase of temperatures resulted in earlier phenological phases and an increasing trend of sugar content while, on the opposite, the acid content decline.

The present study did not detect any trend in precipitation amount during the growing period, in agreement with the results of the local regional analysis (ARPA, 2020) and no significant relationship between harvest timing and rainfall. Nevertheless, beyond the rainfall amount, rainfall temporal distribution affects greatly the grape development and yield (Schultze *et al.*, 2016). Given a similar amount of precipitation during the growing period, variations of temporal rainfall distribution can affect water availability for the crop when water demand is greater, for example in spring, as was detected by Camps and Ramos (2012) in Spain, with significant consequences on the grape development. During the last 2 decades, in Piedmont, very often cumulated precipitation in spring was lower than the reference average over 1971-2000 (ARPA, 2020). Furthermore, temporal rainfall distribution and rainfall characteristics (intensity and duration of rainfall events) play also a relevant role in determining water and soil losses in sloping vineyards of Monferrato (Biddoccu *et al.*, 2017; Bagagiolo *et al.*, 2018), that can result in the decrease of water input, thus in even lower water availability for plant development, and soil degradation. Further investigation is needed to evaluate the effects of variation in precipitation distribution along the year on the water availability and then on crop growth and phenological phases, grape quality and yields in the Monferrato area. Such research will help address vineyard management choices, including adequate soil and water conservation strategies, to achieve more sustainability in vineyards in the current climate change scenario.

5. CONCLUSIONS

This study contributed to understand how climate change and, in particular, the increasing trends of temperatures observed in the last decades are affecting the harvest period of grapevine in the Basso Monferrato wine-growing area. Indeed, mainly the analysis based on the two long-term homogeneous meteorological series of Vezzolano (1962-2004) and Moncalieri (1961-2019), besides confirming a significant, clear, increasing trend of local temperatures, demonstrated a strong relationship between warming temperatures and the anticipation of grapevine development and harvest dates. The beginning harvest dates showed a significant decreasing trend from 11.6 to 34.2 days in 58 years, in line with several previous studies. Furthermore, the results indicated in the most recent 15 years a tendency to anticipate the harvest by 11-13 days for each increase equal to 1 °C in minimum temperature. These findings show clearly the effects of climate warming on grapevine phenology in a district with a long tradition of wine production.

Further studies will apply the proposed analysis to the evolution of grapevine phenological events and other areas and varieties, with regard to temperatures and related bio-climatic indices, and precipitation. In the present analysis, the amount of total precipitation did not show a significant trend. Still, it could be relevant to investigate the effects of temporal rainfall distribution on crop development and production and evaluate water availability in different phenological phases in a region where vineyards are traditionally rainfed. As a final note, the present work highlighted that under a climate change scenario, the availability of continuous and homogenous datasets is crucial to properly assess the impact of climate inter-annual variability on crop management.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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