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Weather trend and impact on sugar accumulation in Montepulciano grapes in a viticultural area of central Italy

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Abstract. The increase in temperatures and frequency of drought summers is reshaping viticulture, favoring cooler and higher-altitude areas while challenging traditional wine-growing regions. This study examines the relationship between climatic variables and sugar accumulation in Montepulciano grapes in Villalfonsina (Abruzzo, Italy) over the period 1998-2022, using data from a cooperative winery and a regional weather station.Results show a significant rise in seasonal temperatures since 2010, with growing degree days (GGDs) increasing by 7.5%, from 1,988 (1998-2009) to 2,135 (2010-2022). High-temperature events (above 30°C and 35°C) doubled and quintupled, respectively, leading to photoinhibition, leaf necrosis and berry dehydration. The day-night temperature range also increased by 40%, negatively affecting metabolic processes such as sugar transport.Harvest dates were highly variable, with 50% of the grapes harvested between September 29 and October 16. Sugar concentrations ranged from 17.3°Babo (2014) to 20°Babo (2022), with recent vintages consistently exceeding 19°Babo, enabling wines with alcohol levels between 13.3% and 13.8%.This research emphasizes the importance of adapting vineyard practices and choosing harvest dates to reduce climate stress and maintain wine quality as the climate continues to change.

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1 Introduction

Rising air temperatures (T) and frequentdrought summerare favouring the production of high-quality wines in cooler areas, including those at higher elevations sites, at the expense of those known to be warmer or at lower elevation sites. New areas, previously considered unsuitable, are in fact becoming increasingly important for quality viticulture, while many of today's wine-producing areas are unfortunately experiencing significant declines in unit yields and quality imbalances[1].For this reason, new plantings require technical updates in terms of grape varieties, rootstocks, training systems, orientation and exposure of slopes, while for vineyards in production it is crucial to use environmental mitigation techniques (e.g. kaolin, biostimulants, shade nets, localized irrigation, dry farming interventions, etc.)[2-3]. The latter are necessary to mitigate the negative effects of weather changes that can no longer be foreseen, such as the acceleration of the technological ripening of grapes, with an increase in the sugar content of the must and therefore in the alcoholic content of the wine, the decoupling of the technological and phenolic ripening, the decrease in the acidic and aromatic contents and the increase in pH of the must, with negative effects on the stability of the wine, as well as the phenomena of dehydration of the berries and sunburn. The analysis of the evolutionary trends of the meteorological parameters, especially when they are long-term, assumes a strategic importance for the purpose of studying the inter-annual variability, which is often the result of the alternation of different types of air circulation and solar activity, as well as to highlight possible points of discontinuity in the meteorological parameters. Such knowledge is the basis for carrying out corrective technical interventions, taking into account the increasing variations of both the optimum and the threshold T at different phenological stages.For example, with respect to air T in recent years, it has been found that: a) cumulative thermal sums of the spring period are correlated with the time of harvest [4]; b) summer T in July-August plays a primary role in sugar accumulation [5]; c) high T's determine the positioning of the ripening period at a less favourable time for the production of quality wines [6]; d) in Burgundy, temperature ranges have been assigned an important role for red wines, while average maximum T's are relevant for white wines [7]. Based on the above, this paper analyses the relationships between weather trends and harvest data during the period 1998-2022 in a homogeneous wine-growing area in Abruzzo Region.

2 Materials and methods

The study was carried out using the archives of the social cooperative winery “Villese” sited in Villalfonsina (CH, Abruzzo region, central Italy), covering the period 1998-2022.A database that reports sugar degree (°Babo) and net weight for each individual conferment of cv. Montepulciano grapes was used. As many as 147,398 grape conferments were analyzed during that period, and in summary, data are reported for the date of grape conferment and the for the average °Babo of the must calculated at 50% of the grape conferment. Daily data of precipitation (P, mm), minimum and maximum air T (Tmin and Tmax, respectively, °C) recorded at the weather station near the winery, affiliated to the climatic monitoring network of the Regional Agrometeorological Center of Abruzzo, were used for the climatic analysis. The daily mean T (Tmed) was calculated as (Tmin+Tmax)/2. Average daily temperature ranges ΔT and average maximum and minimum T were also calculated for the spring (April-June) and summer (July-September) periods. Growing Degree Days(GDD) were calculated based on the Amerine-Winkler index (GDD = (Tmed-10 °C)) during spring (April-June), summer (July-September), and for the entire vegetative-productive cycle (April-September). The occurrence of extreme temperature events was analyzed from April to September by calculating the number of days with Tmax greater than 30 °C (Tmax-30) and 35 °C (Tmax-35).

3 Results and discussion

In the wine-growing area under consideration, the area cultivated with Montepulciano grapes occupies 750 hectares. The vineyards exhibit a high degree of homogeneity, with 80% of the vines trained on Tendone system (distances of 2.5 × 2.5 m; 1,600 vines/hectare) and 87% grafted on K5BB rootstock.

3.1 Agrometereologicalcharacterization of the period 1998-2022

The agrometeorological characterization of the period 1998-2022 shows an increase in T and in the number of days with Tmax above 30°C and 35°C throughout the vegetative-productive cycle (April-September), without significant changes in precipitation (Tables 1 and 2, Figure 1).

Table 1. Average meteorological variables during the period 1998-2022 (rainfall data are cumulative).

Year	Spring (April-June)				Summer (July-September)				Growing season (April-September)	Precipitation (April - September)
	Tmax	Tmin	P	GG	Tmax	Tmin	P	GG	GG	mm
1998	22.4	14.7	125.4	775.0	27.0	19.9	260.0	1244.5	2020	385.4
1999	22.3	15.0	147.4	787.0	26.8	19.8	180.2	1225.8	2013	327.6
2000	22.9	15.8	54.9	859.1	27.3	19.6	206.2	1242.0	2101	261.1
2001	21.8	14.1	124.6	727.5	27.4	19.4	53.2	1234.9	1962	177.8
2002	21.7	14.3	276.6	734.1	25.6	18.0	284.2	1087.8	1821	560.8
2003	23.6	15.4	77.6	892.4	28.0	20.5	188.4	1318.8	2211	266.0
2004	20.3	13.2	214.0	615.3	27.0	19.3	130.6	1212.5	1828	344.6
2005	22.0	14.2	133.4	741.6	26.0	18.6	182.2	1131.4	1873	315.6
2006	22.0	14.2	162.2	739.8	26.7	18.9	214.4	1179.0	1919	376.6
2007	23.2	15.7	61.8	859.7	27.7	19.4	84.6	1252.4	2112	146.4
2008	22.1	14.2	155.2	746.5	27.0	19.3	153.4	1210.0	1957	308.6
2009	22.2	14.6	347.0	765.8	27.5	20.3	73.4	1283.1	2049	420.4
2010	22.9	13.7	105.8	761.6	28.8	19.0	141.6	1286.3	2048	247.4
2011	22.9	12.4	162.8	697.4	30.2	18.3	182.0	1309.6	2007	344.8
2012	24.4	14.2	147.2	846.4	31.1	21.2	220.0	1486.9	2333	367.2
2013	23.6	13.9	162.4	795.4	29.9	19.8	92.8	1370.7	2166	255.2
2014	23.0	13.8	176.0	763.9	28.4	18.8	200.2	1253.0	2017	376.2
2015	24.9	14.5	116.8	891.7	31.3	21.0	86.0	1490.4	2382	202.8
2016	23.2	13.3	159.2	750.0	28.3	18.6	238.8	1243.5	1994	398.0
2017	24.6	13.8	134.4	842.6	29.8	18.9	202.4	1326.9	2169	336.8
2018	24.4	14.2	147.6	843.2	29.4	19.1	331.6	1312.9	2156	479.2
2019	23.0	13.0	274.2	726.2	30.5	19.1	99.8	1367.2	2093	374.0
2020	23.3	12.4	195.4	726.0	29.8	18.7	89.4	1313.8	2040	284.8
2021	23.4	12.1	80.2	724.2	30.3	19.1	121.2	1351.4	2076	201.4
2022	25.0	13.9	97.2	872.5	30.7	19.5	141.0	1393.9	2266	238.2

Table 2. Regression lines for meteorological variables and degree days for the period 1998-2022. The level of significance of the error is indicated as follows: *P < 0.05; ** P < 0.01. *** P < 0.00, ns = not significant.

Season	Variable	Intercept	β	F test	R^2	Sign.
Spring (April-June)	ΔT	-348.8	0.18	105.7	0.82	***
	Tmax	-173.7	0.10	16.6	0.42	***
	Tmin	175.1	-0.08	14.6	0.39	***
	P	-1059.2	0.60	0.10	0.00	ns
	GG	-1158.1	0.96	0.25	0.01	ns
Summer (July-September)	ΔT	-382.7	0.19	78.9	0.77	***
	Tmax	-338.3	0.18	40.1	0.64	***
	Tmin	44.46	-0.01	0.32	0.01	ns
	P	3213.1	-1.52	0.58	0.02	ns
	GG	-14412.7	7.81	13.3	0.37	**
Growing season (April - September)	GG	-15570.9	8.77	6.04	0.21	*
	Tmax-30	-3906.9	1.97	30.9	0.57	***
	Tmax-35	-1146.9	0.57	12.1	0.34	**

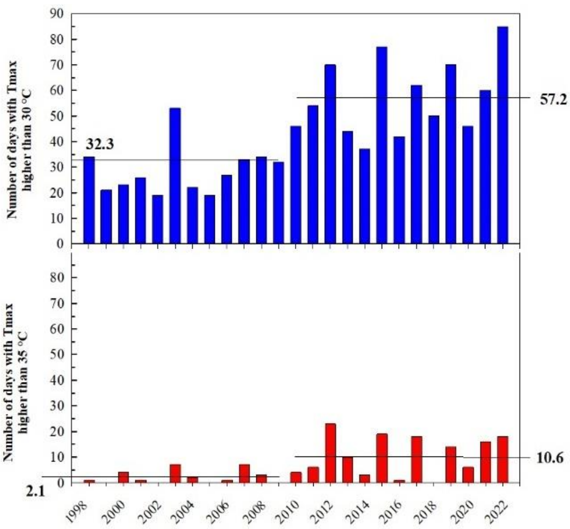

Figure 1. Number of days with maximum air temperature exceeding 30 and 35 °C in the years range 1998-2022.

The evolutionary trends of some weather parameters show a clear increase since the 2010 vintage, in fact, in the last 13 years GGs have increased by 7.5%passing from 1,988 GGs in the 1998-2009 period to 2,135 GGs in the 2010-2022 interval (Table 1). Also compared with the 1998-2009 period, days with Tmax above 30 °C have almost doubled, while those with Tmax above 35 °C have increased by more than 5 times (Figure 1). The latter situation, if prolonged for more than 2-3 consecutive days causes photoinhibition phenomena at the leaf level with chlorosis and necrosis, as well as increased dehydration and sunburn in berries exposed to direct solar radiation (Figure 2).

Figure 2. Montepulciano vineyard with most of the leaves chlorotic and necrotic as a result of chronic photoinhibition caused by thermal and radiative excesses; berries are also strongly dehydrated and affected by sun-burn.

Moreover, it emerges that over the past 13 years (2010-2022), for both the spring and summer periods, there has been a significant increase (by 40% on average) in the day-night average temperature range compared to the 1998-2009 interval (Figure 3).This is caused by significant increases in daytime Tmax in both subperiods examined and an equally significant decrease in night Tmin; however, found to be significant in the April-June period only (Table 2). Reduced night Tmin could adversely affect some growth processes, such as sugar transport, cell division, synthesis of constituent biopolymers of cell walls such as cellulose and lignin, and basic metabolism, which, in many cases, occur during the night, as well as limit cellular respiration with reductions in the production of energy essential for all the processes listed above. Conversely, high Tmax negatively affects photosynthetic activity, which has an optimal range between 20 and 28 °C, and thus the production of sugars that are the engine of plant growth and productivity [8].
As regarding the growing degree sum, a little less than 1/3 of the seasonal values, ranging from a minimum of 1,821 GG in 2002 to a maximum of 2,382 GG in 2015, were calculated for the April-June period (corresponding to the phenological stages from bud burst to blooming time), while the remaining 2/3 in July-September (i.e. during grape ripening) (Table 1). Also at this stage, T exert decisive effects on the sensory profiles of the grapes, the optimum for the

synthesis of primary aromas being in fact 20-24 °C, as well as chromatic since the synthesis of anthocyanins is maximum between 17 and 26 °C[9, 10].The year 2015 was distinguished by the highest thermal availabilities of 892, 1,490 and 2,382 GG for the spring, summer and full cycle periods, respectively, with just 203 mm total rainfall, while 2002 was the coldest vintage, with just 1,821 GG, and 561 mm of cumulative rainfall (Table 1). It is also confirmed that in the years with high rainfall in April-June, fungal pressure was higher, such as 2002 with 277 mm of rainfall, 2004 with 214 mm, 2009 with 347 mm, and 2019 with 274 mm, and of course 2023 with over 460 mm.

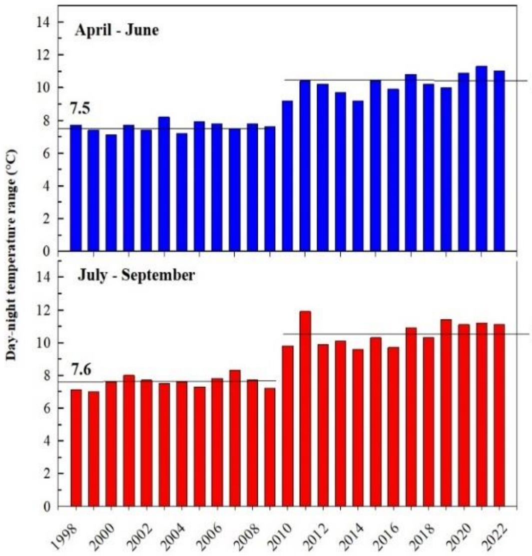

Figure 3. Day-night temperature range during the period 1998-2022 in the spring (April – June) and summer (July – September).

3.2 Grape conferral and sugar concentration

The dates of conferring of Montepulciano grapes were characterized by high variability: 50% of the grapes delivered to the winery occurred between September 29 (recorded in 1998 and 2017) and October 16 in 2004 (Figure 4A). The values of the weighted average °Babo, related to 50% of the delivered grapes, were in the range between the minimum value of 17.3 °Babo recorded in 2014 and the maximum value of 20 °Babo recorded in 2022 (Figure 4B). In the last four years, values have always been above 19 °Babo, coinciding with high thermal levels, especially in 2022 with as many as 2,266 GG. The wine Montepulciano d'Abruzzo DOC appellation indicates a minimum natural alcohol content by volume of 11.5%, which rises to 12% in the Riserva version, so grapes are required to be harvested with a sugar content of 17.1 and 17.8 °Babo, respectively. In all the years considered, in the 50% of the total grapes conferred, these gradations were reached, demonstrating the full suitability of the area under consideration for the cultivation of cv. Montepulciano. Even in the last 4 vintages, i.e., from 2019 to 2022, the sugar content of the musts measured at the conferral of 50% of the grapes varying from 19.3 to 20 °Babo allowed to obtain wines with not particularly high alcohol content, i.e., varying from 13.3 to 13.8%. In general, vintages characterized by high T and limited rainfall in the summer period have higher weighted average sugar content, as in 2007, 2012, 2015, and the last 4 vintages (Figure 4).

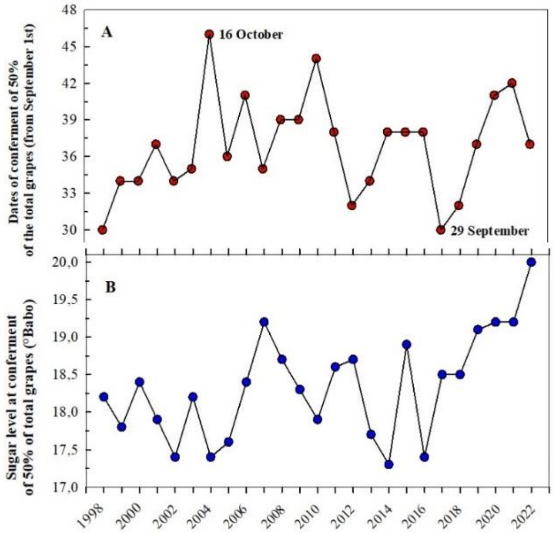

Figure 4. Dates of 50% grape conferring in the period from1998 to 2022 (A). Weighted average sugar content calculated at 50% grape conferring during the time period 1998-2022 (B).

4 Conclusions

The knowledge of the seasonal weather pattern over a sufficiently long period in a defined area, especially if it is homogeneous from technical point of view, is certainly useful for the organization of harvesting dates and wine-making, especially when social cooperatives are considered. In the area analyzed, which is quite homogeneous in terms of grape varieties, rootstocks, training systems and soil characteristics, the variations observed in the dates of grape harvesting and in the sugar content of the musts can be attributed mainly to the annual cycle of weather factors. This variability is especially linked to air temperature trends,also considering that grape yield are relatively stable,ranging from 14 to 17 t/ha. The increase of Tmax and Tminand the number of summer days with T° air higher than 30-35 °C found in the last 4-5 years obliged to the continuous monitoringof sugar accumulation in the grapes. This monitoring activity would help to define the optimal dates of harvest for each vineyard, avoiding unexpressed and immature wines to be madeand/or to apply suitable management techniques to avoid negative effects of environmental stresses.

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