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Phenological characteristics of different winegrape cultivars in Central Italy

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Summary

Statistical models based on temperature accumulation are used to estimate grapevine phenology (e.g. bud break, flowering) through summation of daily heat requirements calibrated from a base temperature and a given date. This study was designed to define the grapevine agro-phenological behaviour through analysis of potential trends of some principal phenological phenomena, such as flowering, harvest, and berry sugar levels at harvest. The data utilized were recorded over a 13-year period (2000-2012) for different grape varieties in the Umbria wine region in central Italy. Moreover, to determine the more important relationships between meteorological variables and recorded data, partial least-squares regressions were carried out.

The trend analysis for berry sugar accumulation shows increasing degrees during the study period that were linked more to the 'Grechetto' cultivar than to the 'Chardonnay' and 'Merlot' cultivars, and then to 'Cabernet'. The statistical model that was focused on the study of the relationships between mean annual berry sugar levels and meteorological variables showed that mean maximum temperatures in April and July are the most important predictive variables for berry sugar accumulation, through their positive influence on berry sugar degree.

K e y w o r d s : grapevine; phenology; flowering; harvest; berry sugar accumulation.

A b b r e v i a t i o n s : GDD, growing degree day; GDD_f, Growing degree days to flowering; DOY, day of the year; °Babo, Babo degree (g sugar·L^{-1}); RMSE, root mean square error; Tmax, mean maximum temp. (°C); Tmin, mean minimum temp. (°C); Pp, total precipitation (mm).

Introduction

The grapevine (*Vitis vinifera* L.) is a woody perennial plant that remains productive for 50 to 60 years, during which time the spring phenological phase of bud break occurs annually over a characteristic range of variety-specific dates (from March to April). This is followed by a period of intensive vegetative growth, during which the shoots arising from the buds elongate and produce leaves very rapidly. The number of viable fruit (berries) that continue development is determined shortly after flowering, at which time the maturing fruit clusters become the primary sinks for the photosynthate. Growing fruits are characterised by their seed development, with the building of the green berry structure and the accumulation of berry sugar which is accompanied by colour change (veraison) and rapid enlargement of the fruit. The times between these phenological stages can vary greatly across the grapevine varieties and the climate and geographic location.

With grapevines, previous studies have used process-based phenological models to describe differences between varieties (Winkler 1962, Oliveira 1998, García de Cortázar *et al.* 2009), advances in phenology (Chuine *et al.* 2004, Nendel 2010, Parker *et al.* 2011) or as a useful basis for pest management (Hoppmann and Berkelmann-Loehnertz 2000). Indeed, meteorological variables such as temperature and precipitation can directly affect the grapevine phenological behaviour (Kishino and Marur 2007, Dalla Marta *et al.* 2010). Combined with radiation, these two factors provide the all-important control of grapevine growth and development, with modifications to the photosynthetic rate, and consequently with effects on the final grape quality and production.

Classically, the spring warming model that is based on the calculation of the growing degrees days (GDD) is the simplest model that has been used to estimate grapevine phenology (e.g. bud break, flowering, veraison). The sum of the daily heat requirements gives a measure of the state of forcing in degrees days (°C·day^{-1}; expressed as units of GDD). Recently, phenological models have been successfully developed for the bud-break stage of the grapevine, which incorporate both chill and heat units (Caffarra and Eccel 2011).

Several studies linked increasing temperature trends with earlier phenological development of many wild and cultivated plants (Chmielewski *et al.* 2004, Menzel *et al.* 2006, Schwartz *et al.* 2006, Orlandi *et al.* 2013a and b). Moreover, different studies have used the grapevine as a bioindicator of changes associated with global temperature warming, because the grapevine is considered to be a highly sensitive crop to weather fluctuations (Jones and Davis 2000, Jones *et al.* 2005, Laget *et al.* 2008, Petrie and Sadras 2008).

When the vegetative and reproductive development of grapevines are well adapted to the local conditions, the grapes at harvest can correspond to the desired combination of berry sugar and acidity, and aromatic and phenolic profiles, or other desired qualities, for the production of high-quality wine (Jones and Davis 2000, Jones *et al.* 2005, Van Leeuwen *et al.* 2008). However, grapevine varieties

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planted in a specific location under certain climate conditions might no longer be adapted to reach maturity under the climate conditions of the future. Therefore, understanding how temperature influences the timing of grapevine vegetative and reproductive development, and identifying specific varietal differences in terms of phenology and maturity, are crucial.

This study was aimed at determining grapevine agro-phenological behaviors through an analysis of the potential trends of the qualitative fruit expression at harvest (berry sugar levels). Flowering and harvest maturation were monitored over a 13-year period (2000-2012) for different grape varieties in the Umbria wine region in central Italy. Temperature summations were calculated to develop a simple process-based agro-phenological model to predict the qualitative level (degree) of the berry sugar content at harvest, while partial least-squares regressions were carried out to determine the more significant relationships between meteorological variables and the biological data.

Material and Methods

Study area and grapevine cultivars: The study was carried out at the farm of the "Foundation for the Agricultural Education in Perugia", located in Marsciano, near the city of Perugia, central Italy (Fig. 1). The study area (around 43° 00′ 40″ N; and longitude, 12° 14′ 52″ E) falls within the production zone 'Colli Perugini DOC' guarantee of origin, and it extends to the right side of the River Tiber, with a climate and an exposure to the south/southeast, and partially protected from the cold winds coming from the north, particularly favorable for viticulture. The soil of the study area generally has a strong clayey calcareous component, which can be seen by the light color of the land. At the farm, which includes about 70 hectares of vineyards and is located at an elevation of 256 m a.s.l., five varieties included in the DOC regulations were studied and included two white cultivars 'Chardonnay' 118 and 'Grechetto' and three red cultivars 'Cabernet Sauvignon', 'Merlot' and 119 'Sangiovese'. All of the grapevines were of clonal origin, grafted onto SO4 ('Sangiovese' and 'Grechetto') and 1103P ('Cabernet Sauvignon' and 'Merlot') rootstock.

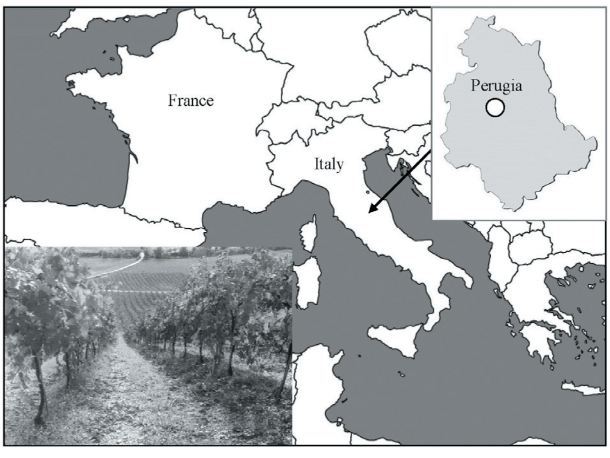

Fig. 1: The study area. Umbria Region (Central Italy).

The training system is in the form of cordons with spurs, which is suitable to promote and facilitate mechanisation of some of the farming operations, such as harvesting and pruning. In this form, the stems reach 60 to 70 cm in height, and then extend horizontally as permanent cordons for a length of about 1 m, with spurs with 2-4 buds every 15 to 30 cm. This is a form of cultivation that is well suited to soils of average fertility, and even to dry soils. Generally the grapevine density is 2,200 to 4,000 plants·ha^{-1}, with an average load of buds from 50,000 plants·ha^{-1} to 80,000 plants·ha^{-1}, and with grapevine rows separated by 2.5 m to 2.8 m, and grapevine plants by 0.8 m to 1.0 m.

Phenological data: The phenological information related to the flowering dates are reported from 2000 to 2012 for all of the grapevine cultivars. In particular, these flowering dates were expressed as 'day of the year' (DOY), as the number of day after January 1st.

The Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie (BBCH) phenological keys were used (Chmielewski and Rötzer 2001). In the present study, the following phenological phases were considered for the reproductive cycle: BBCH65, full flowering (50 % of flowerhoods fallen); BBCH89, berries ripe for harvest.

The harvest dates in particular were recorded along with the qualitative aspects of the berries, considering the berry sugar content, carried out on almost a weekly basis with randomly selected plants indicating the start of the potential harvest period when the berry sugar level on average reached a conventional minimum value (≥ 18 °Babo).

Berry sugar levels: Different measurement units can be used to determine the berry sugar content of grape berries. In our case, the samples of berries were pressed at 0.5 MPa in a pneumatic micropress, and the juice samples were analysed for soluble solids by refractometry. This was expressed as g sugar·L^{-1}, with the subsequent determination of the so-called 'Babo' degree, where each degree corresponds to 10 g sugar in 1,000 g berry juice (Giomo *et al.* 1996). The potential harvest period was determined for each cultivar over the years as when the berry sugar accumulation reached ≥18 °Babo.

Meteorological data: The meteorological data considered in the present study were daily values of temperature, precipitation and evapotranspiration. To summarize the principal climatic influence of the cited variables, monthly mean maximum and minimum temperatures (°C), monthly total accumulated precipitation (mm), and evapotranspiration rate (mm/day) for the months from March to August were calculated.

The meteorological data were obtained from the weather station nearest to the study area; *i.e.* the Italian National Meteorological and Climatological Centre. The weather station is located at an elevation of 229 m a.s.l. (43°01' N, 12°18' E) and is just over 2 km from the study area.

Trend analysis: The presence of phenological and qualitative trends through the study period was investigated using the Mann-Kendall tests, which are non-parametric tests, for monotonic increasing or decreasing trends, not dependent upon the magnitude of data, assumptions of distribution, and missing data (Salmi 2002). In particular, the trends were evaluated using the Z coefficient estimation for each of the variables considered, through the 13 years of data for each variable. Positive Z-values indicate a delaying trend in the phenological data, while negative Z-values indicate an advancing trend.

This type of analysis was also conducted for the monthly temperature means (*i.e.* Tmax, Tmin; °C), the total precipitation (mm), the number of rainy days (> 2 mm·day^{-1}), and the temperature summations (max, min, mean; °C) from January 1st to the end of each month. These data thus provided an evaluation of the trends of the principal meteorological variables through the years of the study.

To estimate the true slope of any existing trends (as change per year), Sen's non-parametric method was used (Sirois 1998). For the four tested levels of significance of the trends, the following symbols are used: **, a = 0.01 (highly significant); *, a = 0.05 (significant); and +, a = 0.1 (nearly significant). All of the trends were calculated using the MAKESENS Excel template, version 1.0 (Microsoft Inc., Redmond, WA).

Temperature summations for the bi-ometeorological relationships: The forcing temperatures and their variability during the study period were evaluated calculating annual GDD amounts and related coefficients of variation (CV). The GDD (°C·day^{-1}) were calculated using the method proposed by Arnold (1960), which is based on the maximum and minimum temperatures.

According to recent studies (Parker *et al.* 2011), the state of forcing is described as a daily sum of the rate of forcing, R_f, that starts on t_0 (DOY), with x_t as the daily mean temperature. The rate of forcing in the spring warming model is defined by equation:

$$R_f(x_t) = \mathrm{GDD}(x_t) = \begin{cases} 0 & \text{if } x_t < Tb \\ x_t - Tb & \text{if } x_t \geq Tb \end{cases}$$

where Tb is the base temperature above which the thermal summation is calculated. Parker et al. (2011) optimized the spring warming model with a base temperature of 0 °C calculated from DOY 60 (t_0). However, to determine the values of the equation parameters that are better adapted to the study area, different forcing start dates and threshold temperatures were tested: February 15 (DOY 46), March 1 (DOY 60) and March 15 (DOY 74) as forcing start dates, and 0, 1, 2, 3, 5, 7, 10 and 12 °C as threshold temperatures. Finally the best forcing start date and threshold temperature were defined minimizing the CVs for modeling the berry sugar levels at harvest.

Partial least-squares regressions for the berry sugar level–meteorological relationships: To define the most significant relationships between the better forcing amounts (evidencing the lowest CVs during the 13-year period), the meteorological parameters, and the berry sugar degree, three regression models were constructed using the partial least-squares regression technique. A first model considered all the cultivars together (model A), a second model (B) considered the white grapes ('Chardonnay' and 'Grechetto') and the last model (C) the red grapes ('Cabernet', 'Merlot' and 'Sangiovese'). The annual berry sugar degrees for all of the cultivar measurements were considered as the dependent variables and the meteorological parameters as the independent variables. The modelling was based on linear transformation of the original descriptors to a small number of orthogonal factors (latent variables), to maximise the covariance between the descriptors and the dependent variables. This procedure provides the optimal linear model in terms of the forecasting. In the present study, each latent variable represented a key factor for the grape sugar degree. Once the models were obtained, the regression equation was used to determine the exact weight of each meteorological variables in the final sugar accumulation.

The models were validated following a full cross-validation method, which is a statistical method for the evaluation and comparison of learning algorithms. This divides the data into two groups: one dataset is used to train the models, and the other is used to validate the models (Refaeilzadeh *et al.* 2009). The advantage of using this validation method was that there was no need to exclude any year for the construction of the statistical models (Unscrambler 9.7 and the Statistica 7.0 software utilized).

Results

Phenological data and berry sugar content: There are many factors that can affect the grapevine sugar content. These certainly include the climate, but also the yield, the same nature of the grape varieties and their responses, the soil, and the grapevine growing methods.

Tab. 1 summarizes the information on the phenological phases, first in terms of the flowering dates of the grapevine cultivars studied. These dates are reported as means over the 13-year period, and show that the two white cultivars, 'Chardonnay' and 'Grechetto', are clearly more advanced in comparison to the three red cultivars ('Cabernet', 'Merlot' and 'Sangiovese'). Flowering has advanced between 5 to 10 d for 'Sangiovese', with the most delayed being 'Cabernet'. The standard deviations of the five cultivars are similar, with only 'Grechetto' showing greater flowering homogeneity during the study period.

The harvest dates and the berry sugar degrees are also reported in Tab. 1, again as the means over the 13-year study period. A “T-Test - one sample or paired” was utilized to test the differences between the cultivars and really the conclusions from checking the assumptions were that the data are continuous and the differences are normally distributed, not evidencing advances or delays statistically significant. Finally, the mean berry sugar degree recorded at the harvest dates was always >18 °Babo, from the 18.6 °Babo of 'Sangiovese', to the 20.1 °Babo of 'Merlot'. The sugar degree variability was very low, with standard deviations around 1.0 °Babo.

Trend analysis: The trend analysis from the phenological data and the berry sugar degree through the 13-year study period are shown in Tab. 2. All trends for phenological dates or berry sugar degrees were analyzed using Mann-Kendall tests. The significance levels obtained are reported for each wine cultivar in terms of their differ-

Table 1

Descriptive statistics for the flowering and harvest dates, and mean berry sugar degrees at harvest for each grapevine cultivar through the 13-year study period (2000-2012)

Cultivar	Flowering date[a] (DOY)		Harvest date[b] (DOY)		Berry sugar degree[c] (°Babo)	
	Mean	± SD	Mean	± SD	Mean	± SD
Chardonnay	May 16	3.46	August 30	5.06	19.2	0.89
Grechetto	May 15	2.10	September 16	6.56	19.5	0.71
Cabernet	May 25	3.62	September 29	6.09	19.9	1.15
Merlot	May 23	2.96	September 08	4.27	20.1	1.20
Sangiovese	May 20	3.29	September 3	7.02	18.6	1.31

[a], 50 % of the flowers open, expressed as 'day of the year'; [b], expressed as 'day of the year'; [c], 1.0 °Babo corresponds to 10 g sugar in 1,000 g berry juice; SD, standard deviation.

Table 2

Mann-Kendall test results for the phenological data and the berry sugar degree over the 13-year study period (2000-2012). The significance levels obtained are reported for each grapevine cultivar

Cultivar	Flowering date			Harvest date			Berry sugar degree		
	Test Z	Sign.	Q	Test Z	Sign.	Q	Test Z	Sign.	Q
Chardonnay	1.78	+	0.57	0.74		0.23	2.57	*	0.17
Grechetto	1.49		0.29	0.12		0.05	2.62	**	0.15
Cabernet	1.66	+	0.50	-1.78	+	-0.45	1.65	+	0.14
Merlot	1.73	+	0.50	-0.37		-0.13	2.26	*	0.23
Sangiovese	2.32	*	0.72	-1.90	+	-1.00	1.16		0.17

Sign., level of significance: **, a = 0.01; *, a = 0.05; +, a = 0.1. A positive (negative) value of Z indicates an upward (downward) trend. Q indicates the true slope of an existing trend (as change per year).

ent behaviours. In terms of flowering, only one cultivar, 'Sangiovese', showed an evident increasing trend regarding the dates of the flowering phase (test Z, 2.32), which is interpreted as a tendency towards delay through the 13-year study period. Delayed trends were also recorded for three of the other cultivars, *i.e.* 'Chardonnay', 'Cabernet' and 'Merlot' (test Z, 1.78, 1.66, 1.73, respectively), although these trends were not statistically significant.

The harvest dates showed only two nearly significant negative Z-values (*i.e.* decreasing trends) for the 'Cabernet' and 'Sangiovese' cultivars (test Z, -1.78, -1.90, respectively).

The trend analysis for the berry sugar degree (Fig. 2) showed some highly significant data that are primarily linked to the 'Grechetto' cultivar (test Z, 2.62), more than to the 'Chardonnay' and 'Merlot' cultivars (test Z, 2.57, 2.26, respectively), and finally to the 'Cabernet' cultivar (test Z, 1.65). All of the Z-values were positive, which suggests that there were increasing trends of berry sugar through the 13-year study period, with the exception being the 'Sangiovese' cultivar which was not statistically significant.

Daily heat requirements: The variability analysis carried out through the coefficients of variation, considering both the different forcing start dates and the various threshold temperatures, showed, for all of the cultivars, the best forcing start date (t_0) was March 15 (DOY 74) and the best threshold temperature (Tb) was 0 °C (Tab. 3). The mean thermal requirements from March 15 to the flowering date ranged from a minimum value of 823 GDD for the 'Grechetto' cultivar to a highest value of 1,010 GDD for the 'Cabernet' cultivar. In the same way, the mean thermal requirements from March 15 to the harvest date varied from 3,244 GDD for the 'Chardonnay' cultivar to 3,845 GDD for the 'Cabernet' cultivar.

A mean thermal requirement of 2,674 ± 208 GDD was observed between the mean flowering date (DOY 140; May 20) and the mean harvest date (DOY 258; September 15). The 'Sangiovese' and 'Cabernet' cultivars had the highest heat requirements to reach the optimal berry sugar degrees (>2,800 GDD) (Fig. 3). 'Chardonnay' was the cultivar which showed the lowest thermal requirement (< 2,410 GDD).

Biometeorological relationships through partial least-squares regressions: The statistical models for studying the relationships between the mean annual berry sugar degrees at harvest and the meteorological variables revealed significant results. In particular, the significance of the model that considered together all the grapevine cultivars (model A) was high, showing a determination coefficient value of $R^2 = 0.90$ while the determination coefficient of the full cross-validation ($Q^2 = 0.81$) indicates the optimal

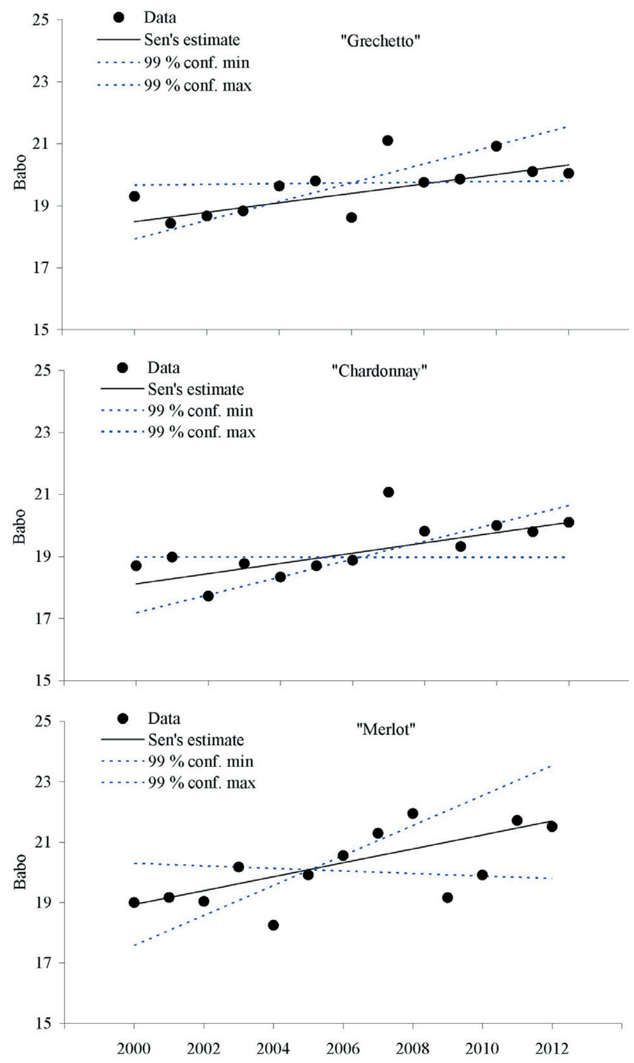

Fig. 2: The more significant Mann-Kendall test results considering the berry sugar degree (°Babo) at harvest, as seen for cultivars 'Grechetto', 'Chardonay' and 'Merlot'.

accuracy of the model. Although the highest significance was obtained for the general model (A), model B, considering together just the white grapes, and model C for the red grapes showed good determination values, with R^2 = 0.82-0.78 and Q^2 = 0.68-0.64 respectively. In all the three models the most important predictive variables for the berry sugar degree formation were spring temperature accumulation to flowering (GDD_f), the total precipitation in April (Pp_A) and the mean maximum temperatures in July (Tmax_J). The coefficients values of the independent variables are shown in Fig. 4. The temperature variables revealed positively related with berry sugar degree while precipitation showed a negative influence. The observed and expected values of the yearly berry sugar degrees predicted by the regression models are reported in Fig. 4, with the respective regression formulas. The deviation between the observed and predicted berry sugar degree values obtained by the model A (as absolute values) was between 0.3 % (2010) and 4.1 % (2001), between 0.4 % (2005) and 3.7 % (2007) with the model B and between 0.1 % (2002) and 5.8 % (2001) with the model C.

Table 3

Coefficients of variation of annual GDD amounts considering three forcing start dates (February 15 and March 1 and 15) and eight threshold temperatures for each of the cultivars

	Threshold temp. (°C)	CV of ΣGDD at flowering			CV of ΣGDD at harvest		
		February 15	March 1	March 15	February 15	March 1	March 15
Chardonnay	0	10	10	9	4	4	4
	1	10	11	10	4	4	4
	2	11	12	10	4	4	4
	3	11	12	11	4	4	4
	5	13	14	12	5	5	5
	7	15	16	15	5	5	5
	10	20	20	20	6	6	6
	12	25	25	26	8	8	8
Grechetto	0	9	9	8	3	3	3
	1	9	9	8	3	3	3
	2	10	10	9	3	4	4
	3	11	11	10	4	4	4
	5	13	13	11	4	4	4
	7	15	15	14	4	5	4
	10	20	20	20	5	5	5
	12	25	26	26	7	7	7
Cabernet	0	9	9	8	3	3	3
	1	9	9	9	3	3	3
	2	10	10	9	3	3	4
	3	10	10	10	3	4	4
	5	11	12	10	4	4	4
	7	13	13	12	4	5	5
	10	16	16	16	6	6	6
	12	20	20	21	8	8	8
Merlot	0	9	9	8	3	3	3
	1	9	9	8	3	3	3
	2	10	10	8	3	3	3
	3	10	10	9	3	4	3
	5	12	12	10	4	4	4
	7	14	14	12	4	4	4
	10	18	18	17	6	6	6
	12	22	22	22	7	7	7
Sangiovese	0	9	9	8	5	5	4
	1	9	9	9	5	5	4
	2	10	10	9	5	5	5
	3	10	10	10	5	5	5
	5	12	12	11	5	5	5
	7	14	14	13	6	6	5
	10	18	19	18	7	7	7
	12	23	23	23	8	8	8

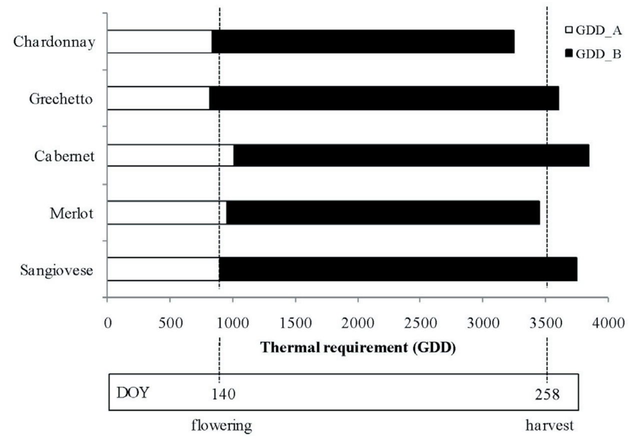

Fig. 3: The thermal requirements for the flowering and harvesting. GDD_A, GDD from March 15 (t_0) to mean flowering date (DOY 140); GDD_B, GDD from the mean flowering date to mean harvest date (DOY 258).

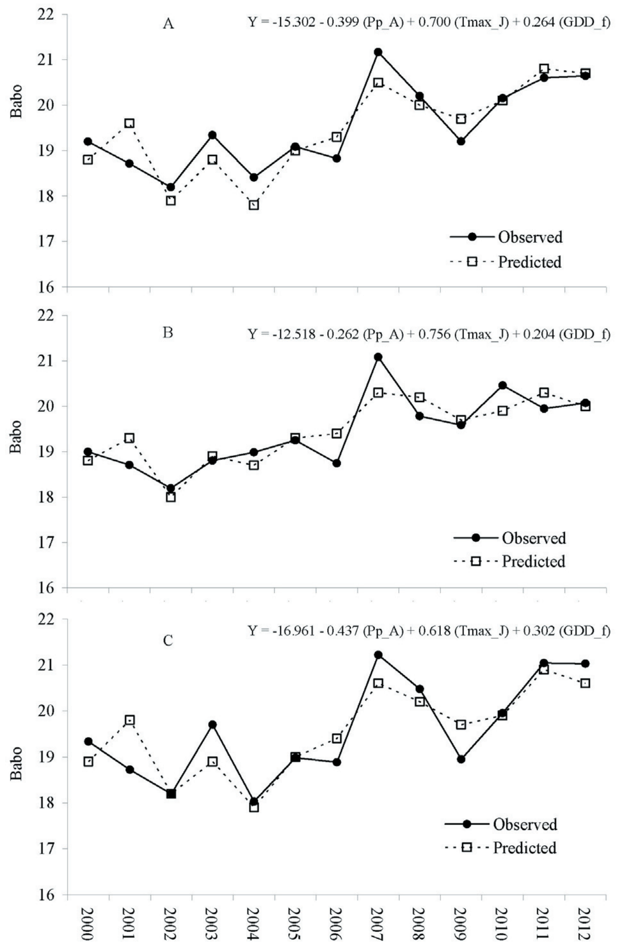

Fig. 4: Observed and predicted annual berry sugar degrees through the 13-year study period (2000-2012). Pp_A, total precipitation in April; Tmax_J, mean maximum temperature for July; GDD_f, Growing degree days to flowering. The regression equations are shown for each model: **A**:General model; **B**: White grape model; **C**: Red grape model.

Discussion

The present study has provided an evaluation of the thermal requirements for flowering, harvesting and berry sugar accumulation in grapevine cultivars that are typically cultivated in the Umbria winegrowing region in central Italy. Comparisons with other studies are difficult, considering the differences in the phenological phases recorded (*i.e.* veraison or harvest), and the parameters of the phenological models (*i.e.* start temperature accumulation dates, threshold temperatures). For example, a recent study of PARKER *et al.* (2011) considered the mean thermal requirements from March 1 to their flowering and veraison dates, while in the present study, the best start temperature accumulation date was March 15, and no veraison data were available. Some comparisons about forcing temperature requirements of four common vine cultivars ('Chardonnay', 'Merlot', 'Sangiovese' and 'Cabernet') can be carried out considering another work (PARKER *et al.* 2013). In particular in the Parker investigation the starting date for the temperature amounts was advanced of 15 d in comparison to that utilized in the present study and this difference probably determined the lower temperature summations to flowering (all the cultivars evidenced values around 1,000 GDD in our experience and around 1,200 in the Parker work). On the other hand the temperature requirements in the successive fruit maturation phases were different (in our experience the cultivar requirements ranged between 3,200 and 3,800 GDD and between 2,500-2,700 in the Parker work), considering that fruit harvesting is realized some weeks after veraison which phenological phase is BBCH 81 (Beginning of ripening: berries begin to develop variety-specific colour). However, in both investigations the white cultivar 'Chardonnay' showed lower thermal requirements than the red cultivars to reach flower development and fruit maturity.

The trend analyses showed that the berry sugar degrees has increased over the 13-year study period for almost all of the grapevine cultivars considered, also when harvest dates not varied significantly. Only 'Sangiovese' did not show a significant increase in berry sugar degrees, although in this case the flowering delay and the harvest advance reduced the fruit maturation period influencing the sugar accumulation.

The vintage climatic conditions can influence the grape quality through the temperature requirements or the water balance, with high sunlight stimulating anthocyanin accumulation in the berries (KELLER and HRAZDINA 1998, BERGQVIST *et al.* 2001, SPAYD *et al.* 2002). In the present investigation the temperature requirements during the flower structure formation, in particular during April, were positively linked to the harvested berry sugar levels. Probably the spring temperature accumulation has a positive effect on flowering, inducing an advance in flower growth and opening. This phenomenon permits a concomitant advance of the fruit setting phase and the realization of the first berry sugar accumulation during a period in which summer stress is not as high compared to those of July or August in mediterranean climate conditions.

Moreover, from a climatic point of view there are clear relationships between improved grape quality (berry sugar) and water deficit recorded in April, when it probably affects the grape quality indirectly, with an early water deficit causing early shoot vegetative growth cessation, and consequently inducing reproductive utilization of the assimilates for flowering advance. In literature is clearly indicated that a moderate restricted water supply improves the wines quality by causing the grapes to achieve optimal sugar levels, encouraging rapid ripening while restricting the size of the berries (VAN LEEUWEN *et al.* 2009). It also consents to a greater percentage of the sugars produced by photosynthesis to be available for grape ripening (LEBON *et al.* 2006). As a consequence the ideal water uptake conditions for producing high quality grapes for making red wine corresponds to a moderate water deficit early in the season. Generally, drought between flowering and fruit setting reduces the number of berries and the yield, without changing the berry sugar content, drought after fruit setting reduces the berry weight and yield, and drought at the fruit colouring phase diminishes the berry weight and increases the sugar levels (Van Leeuwen *et al.* 2004). Moreover, many studies have shown the positive influence of high temperatures (> 30 °C) in berry sugar increases (Bergqvist *et al.* 2001, Sadras and Moran 2012). According to the present study, high temperatures during early summer can stimulate the young fruit development considering the presence of yet sufficient water availability and good leaves photosynthetic efficiency. In this manner, the presence of an increasing sugar trend over the 13-year study period was recorded along with an increasing maximum temperature trend during July.

The detailed analysis of the two most important temperature variables in terms of the final sugar accumulation in the berries suggested some considerations. When the lowest temperature values recorded during the study years were manifested during both spring (GDD) and summer (Tmax_J) of the same year (2002), the final sugar degree did not reach beyond 18.5 °Babo (although this remains higher that the lowest limit for harvesting, of 18 °Babo), while during the warmest year (2007), the sugar level reached nearly 21 °Babo. However, the more influential variable appeared to be the mean maximum temperature during July, even though this also showed a very narrow interval of variation during the study period, of only 1.8 °C (from 30.6 °C to 32.4 °C).

Conclusion

The present study confirms the importance of specific periods in the development of the reproductive structures (*i.e.* the flowers and berries) as critical for the final sugar accumulation rate experienced in these cultivars in the Umbria winegrowing region of central Italy. This sugar accumulation, and consequently the berry sugar content, is indeed the first element of quality, and it is a complex process that is the result of many components. The berry sugar content is thus a good indicator of the berry quality, manifesting the developments of ripening, during which the other quality components will be developing in parallel. In these terms this study proposes a predictor model to evaluate grape quality potential in viticulture, in relation to the occurrence of water and forcing temperatures during pre and post flowering (April-June) – fruit setting (July) periods.

This early evaluation could permit to manage water reserves in the soil regulating a correct occurrence of water deficit, adopting particular agronomic techniques (presented in literature) such as the leaf area per hectare increase in order to amplify evapotranspiration (increasing the trimming height or changing the trellis system). Other potential techniques to adopt could be the vine density increase or the selection of rootstocks which only partially use water reserves of the soil. On the other hand, in very dry climates, when the annual rainfall is poor and not adequately distributed in flowering-fruit setting periods, well managed irrigation can improve grape quality potential driving the vine progressively into a situation of moderate water deficit but avoiding excessive water stress.

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References

Arnold, C. Y.; 1960: Maximum-minimum temperature as a basis for computing heat units. J. Am. Soc. Hortic. Sci. **76**, 682-692.

Bergqvist, J.; Dokoozlian, N.; Ebisuda, N.; 2001: Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the Central San Joaquin Valley of California. Am. J. Enol. Vitic. **52**, 1-7.

Caffarra, A.; Eccel, E.; 2011: Projecting the impacts of climate change on the phenology of grapevine in a mountain area. Aust. J. Grape Wine Res. **17**, 52-61.

Cawthon, D. L.; Morris, J. R.; 1982: Relationship of seed number and maturity to berry development, fruit maturation, hormonal changes, and uneven ripening of Concord (*Vitis labrusca* L.) grapes. J. Am. Soc. Hortic. Sci. **107**, 1097-1104.

Chmielewski, F. M.; Müller, A.; Bruns, E.; 2004: Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. Agric. For. Meteorol. **121**, 69-78.

Chuine, I.; Yiou, P.; Viovy, N.; Seguin, B.; Daux, V.; Ladurie, E. L.; 2004: Historical phenology: grape ripening as a past climate indicator. Nature **432**, 289-290.

Dalla Marta, A.; Grifoni, D.; Mancini, M.; Storchi, P.; Zipoli, G.; Orlandini, S.; 2010: Analysis of the relationships between climate variability and grapevine phenology in the Nobile di Montepulciano wine production area. J. Agric. Sci. **148**, 657-666.

García de Cortázar, I.; Brisson, N.; Gaudillere, J. P.; 2009: Performance of several models for predicting bud burst date of grapevine (*Vitis vinifera* L.). Int J Biometeorol **53**, 317-326.

Giomo, A.; Borsetta, P.; Zironi, R.; 1996: Grape quality: research on the relationships between grape composition and climatic variables. Acta Hortic. **427**, 277-286.

Hoppmann, D.; Berkelmann-Loehnertz, B.; 2000: Prognosis of phenological stages of *Vitis vinifera* (cv. Riesling) for optimizing pest management. EPPO Bull. **30**, 121-126.

Jones, G. V.; Davis, R. E.; 2000: Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Vitic. **51**, 249-261.

Jones, G. V.; White, M. A.; Cooper, O. R.; Storchmann, K.; 2005: Climate change and global wine quality. Clim. Change **73**, 319-343.

Keller, M.; Hrazdina, G.; 1998: Interaction of nitrogen availability during bloom and light intensity during veraison: II. Effects on anthocyanin and phenolic development during grape ripening. Am. J. Enol. Vitic. **49**, 341-349.

Kishino, A.; Marur, Y. I.; 2007: Factores climáticos y desarrollo de vides. En: A. Kishino, S. Carvalho y S. Roberto (Red.): Viticultura tropical, 59-86. Londrina: IAPAR.

Laget, F.; Tondut J. L.; Deloire A.; Kelly M. T.; 2008: Climate trends in a specific Mediterranean viticultural area between 1950 and 2006. J. Int. Sci. Vigne Vin **42**, 113-123.

Lebon E., Pellegrino A., Louarn G., Lecoeur J.; 2006: Branch development controls leaf area dynamics in grapevine (*Vitis vinifera*) growing in drying soil. Ann. Bot. **98**, 175-185.

Menzel, A.; Sparks, T. H.; Estrella, N.; Koch, E.; Aasa, A.; Ahas, R.; Alm-Kübler, K. Bissolli, P.; Braslavská, O.; Agrita Briede8, Chmielewski, F. M.; Crepinsek, Z.; Curnel, Y.; Dahl, Å.; Defila, D.; Donnelly, A.; Filella, Y.; Jatczak, K.; Måge, F.; Mestre, A.; Nordli, Ø.; Peñuelas, J.; Pirinen, P.; Remišová, V.; Scheifinger, H.; Striz, M.; Susnik, A.; Van Vliet, A. J. H.; Wielgolaski, F. E.; Zach, S.; Zust, A.; 2006: European phenological response to climate change matches the warming pattern. Glob. Change Biol. **12**, 1969-1976.

Nendel, C.; 2010: Grapevine bud break prediction for cool winter climates. Int. J. Biometeorol. **54**, 231-241.

Oliveira, M.; 1998: Calculation of budbreak and flowering base temperatures for *Vitis vinifera* cv. Touriga Francesa in the Douro region of Portugal. Am. J. Enol. Vitic. **49**, 74-78.

Orlandi, F.; Garcia-Mozo, H.; Ben Dhiab, A.; Galán, C.; Msallem, M.; Romano, B.; Abichou, M.; Dominguez-Vilches, E.; Fornaciari, M.; 2013a: Climatic indices in the interpretation of the phenological phases of the olive in mediterranean areas during its biological cycle. Clim. Chang. **116**, 263-284.

Orlandi, F.; Garcia-Mozo, H.; Ben Dhiab, A.; Galán, C.; Msallem, M.; Fornaciari, M.; 2013b: Olive tree phenology and climate variations in the Mediterranean area over the last two decades. Theor. Appl. Climatol. **115**, 207-218.

Parker, A. K.; De Cortázar-Atauri, I. G.; Van Leeuwen, C.; Chuine, I.; 2011: General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. Aust. J. Grape Wine Res. **17**, 206-216.

Parker, A.; Garcia De Cortazar Atauri, I.; Chuine, I.; Barbeau, G.; Bois, B.; Boursiquot, J. M.; Cahurel, J. Y.; Claverie, M.; Dufourcq, T.; Geny, L.; Guimberteau, G.; Hofmann, R. W.; Jacquet, O.; Lacombe, T.; Monamy, C.; Ojeda, H.; 2013: Classification of varieties for their timing of flowering and veraison using a modelling approach: A case study for the grapevine species *Vitis vinifera* L. Agric. For. Meteorol. **180**, 249-264.

Petrie, P. R.; Sadras, V. O.; 2008: Advancement of grapevine maturity in Australia between 1993 and 2006: putative causes, magnitude of trends and viticultural consequences. Aust. J. Grape Wine Res. **14**, 33-45.

Refaeilzadeh, P.; Tang, L.; Liu, H.; 2009: Cross-Validation. In: Encyclopedia of Database Systems. 532-538.

Salmi, T.; 2002: Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates: The Excel Template Application MAKESENS. ISSN 1456-789X. Finnish Meteorological Institute.

Sadras, V. O.; Moran, M. A.; 2012: Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. Aust. J. Grape Wine Res. **18**, 115-122.

Schwartz, M. D.; Ahas, R.; Aasa, A.; 2006: Onset of spring starting earlier across the Northern Hemisphere. Glob. Change Biol. **12**, 343-351.

Spayd, S. E.; Tarara, J. M.; Mee, D. L.; Ferguson, J. C.; 2002: Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. Am. J. Enol. Vitic. **53**, 171-182.

Van Leeuwen, C.; Friant, P.; Choné, X.; Tregoat, O.; Koundouras, S.; Dubourdieu, D.; 2004: Influence of climate, soil, and cultivar on terroir. Am. J. Enol. Vitic. **55**, 207-217.

Van Leeuwen, C.; Garnier, C.; Agut, C.; Baculat, B.; Barbeau, G.; Besnard, E.; Bois, B.; Boursiquot, J. M.; Chuine, I.; Dessup, T.; Dufourcq, T.; Garcia-Cortazar, I.; Marguerit, E.; Monamy, C.; Koundouras, S.; Payan, J. C.; Parker, A.; Renouf, V. R. L.; Roby, B.; Tonietto, J. P.; Trambouze, J. W.; 2008: Heat requirements for grapevine varieties are essential information to adapt plant material in a changing climate, 222-227. In: Proc. VIIth Int. Terroir Congr., Changins, Switzerland.

Van Leeuwen, C.; Trégoat, O.; Choné, X.; Bois, B.; Pernet, D.; Gaudillère, J. P.; 2009: Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? J. Int. Sci.Vigne Vin, **43**, 121-134.

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