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'Tannat' (*Vitis vinifera* L.) as a model of responses to climate variability

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Summary

Climate variability influence on the vine is widely studied for its impact on grape final composition and quality. During 1994-2016, thermal and water regimes and their influence on grapevine yield, sanitary status and berry composition were analyzed for 'Tannat' grown in commercial vineyards in the south of Uruguay (Lat 34° 37' S; 56° 17' W). Statistical analysis showed that the principal component analysis (PCA) separated years in three groups: Group 1: rainfall over the growing season higher than the average, limited sanitary status, acidity and yield higher than average, lower sugar content, late harvest. Group 2: greater thermal conditions and water component lower than average, better sanitary status, sugar contents and acidity lower than average, early harvest. Group 3: thermal conditions lower than average, rainfall higher during budbreak-fruitset period and lower than average in the month before harvest, berry size and sugar contents greater than average. Correlations between climate, yield and berry quality variables were established and stages of greater sensitivity to these climate elements were determined. In the studied years, climate variability within the region was high and 'Tannat' showed to be strongly influenced by such variability.

Key words: climate variability; yield; sanitary status; berry composition; 'Tannat'.

Introduction

Grapevine is a plant considered as an indicator for climate variability. In the south of Uruguay (Lat 34° 37' S; 56° 17' W) a greater interannual rainfall variability is expected, particularly during the grape ripening period, as well as a raise in the medium temperature (Tiscornia *et al.* 2016). This condition determines yield and grape composition, and favors fungal diseases that cause clusters rotting leading to distortion in the production and grape quality (Chuine *et al.* 2004, Mira de Orduña 2010). Yield variations depend mainly on the cluster number that were induced in the previous season. This physiological process occurs in the bud during the flowering period of the current season and it requires reserves, whose movement depend mainly on a non-limiting water supply (Guilpart *et al.* 2014). Berry weight is one of the yield components mainly affected by maturation temperature and water availability in its first development stage (Ojeda *et al.* 2001, Ferrer *et al.* 2014). According to van Leeuwen *et al.* (2004), meteorological conditions explain more than 80 % of grape composition variability. Temperature during maturation has a direct impact on the organic acids degradation (Sadras *et al.* 2013). Temperatures over 25-30 °C could limit photosynthesis and therefore sugar accumulation in the berry. Rainfall has either a negative or positive effect on sugars and acids content depending on the cultivar cycle stage (Greer and Weston 2010, Hunter and Bonnardot 2011).

Uruguay is among the countries where climate change is affecting interannual rainfall variability, particularly during the grape-ripening period, as well as increasing the average temperature (Tiscornia *et al.* 2016, Fourment *et al.* 2018). In this country, bunch rot is the fungal disease that causes the greatest losses in yield and grape quality due to predisposing factors to infection: abundant rainfall and cool thermal situations during maturation (Ferrer *et al.* 2011, Steel *et al.* 2013). 'Tannat', Uruguay's emblematic variety, provides red wines of great character and originality and, according to annual conditions, expresses its oenological potential differently (González-Neves *et al.* 2004), therefore, providing an important opportunity to study the effect of climate variability. This study aimed at determining the influence of the variability of thermal and water regimes on yield, sanitary status and grape composition of 'Tannat' variety. It is considered an indicator plant in a changing climate context during a 23-year period (1994-2016). The most sensitive cultivar stages to these climate elements were analyzed.

Material and Methods

Plant material and study sites: Field information came from three plots of 'Tannat' commercial vineyards with SO4 as rootstock, managed with vertical shoot positioning (VSP) and with double Guyot pruning, with N-S row orientation, located in the south of Uruguay (Lat 34° 37' S; 56° 17' W). This region's viniculture climate was identified as "moderately dry, temperate warm, temperate nights" (MCC system) (Ferrer *et al.* 2007), under marine breeze influence from the Río de la Plata estuary (Fourment *et al.* 2017).

Variables data: Information on climatic variables were taken from a Meteorological Station (Lat 34° 40' S,

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56° 20' W) database managed according to WMO standards, located in the study region. To compare thermal and water conditions of the studied years, the historical average of variables from the Station between 1972-2015 was considered (Tab. 1). Daily sum of temperature (Degree days base 10 °GDDrip) was calculated during ripening; number of days from January 1st until harvest (Ndrip) and the number of days with temperatures above 30 °C (ND30nh) were counted.

Plant and grape composition analyses: The yield (Y) was evaluated at harvest in 30 individually weighed plants. Healthy and infected grapes were differentiated and the percentage of the latter in the total was calculated (% yield). The "infected" state was defined as bunches that presented more than 5 % incidence of cluster rot. Berry weight (BW) (Ohaus Scout scale, Ohaus Corp., USA) was obtained from two double samples of 250 berries in each vineyard collected according to the protocol proposed by Carbonneau *et al*. (1991).

Regarding technological maturity on the two double samples of 250 berries, weight was measured, as well as soluble solids (SS), using a refractometer (Atago, Master-T, Japan) and total acidity (TA) by titration (Mohr Burette) according to the OIV method (2014). Considered variables are presented in Tab. 1.

Statistical analysis: Data were analyzed using univariate and multivariate statistical analysis. A correlation analysis was performed using Pearson's correlation coefficient and an analysis of variance was performed by Fisher test for mean separation. The multivariate statistical analysis such as Principal Component Analysis (PCA) and Canonical Discriminant Analysis (CDA) were performed to group years through significant correlations between meteorological conditions and yield, berry composition and sanitary status. Using single and multiple linear regression models, the plant response variables (Y, BW, TA, SS and %ig) were modeled in a general context of analysis and taking into account the classification suggested by the PCA (group 1, 2 and 3). The best explanatory models were selected through step-wise selection by setting inclusion limits of the model parameters of 0.10 (*p*-value). Tests were performed to demonstrate the compliance with the assumptions of the model (linearity, homocedasticity of variance, independence and normality). All statistical analyses were carried out using the InfoStat software.

Results

The influence of climate interannual variation on plant response and grape composition was evidenced, generating a grouping of the studied years.

Variation of thermal and water regime. Group of years: The PCA analysis showed that the first two principal components explained 48.2 % of the total variance (Fig. 1). The principal component 1 (PC1) contributed 28.5 % while the principal component 2

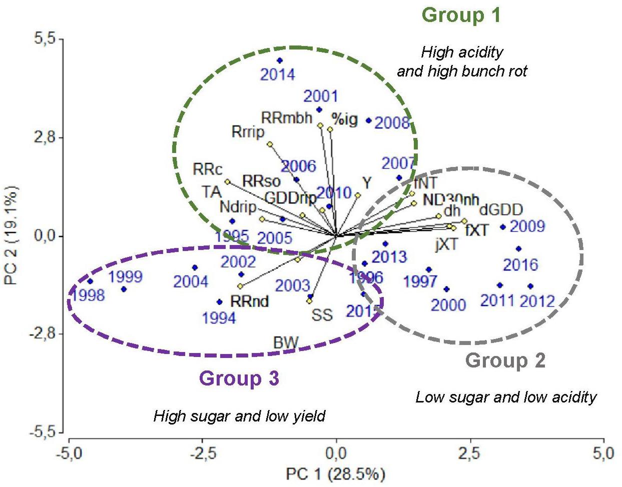

Fig. 1: Principal Component Analysis (PCA). Eigen vectors of climate variables and plant reponse (yellow) and medium scores for each year (blue). Abbreviations are listed in Tab. 1.

Table 1

References of the variables used in the study

Variable	Reference
January Maximum Temperature (°C)	jXT
February Maximum Temperature (°C)	fXT
February Minimum Temperature (°C)	fNT
Daily sum of temperature during ripening (Degree days, °C)	GDDrip
Daily sum of temperature Days during ripening (Degree days °C)	dGDD
Number of Days of Temperatures above 30 ºC (November to harvest)	ND30nh
Accumulated radiation from budburst to fruit set in the precedent year ($cal \cdot cm^2 \cdot day^{-1}$)	ARbd-fsA-1
Rainfall in September and October (mm)	RRso
Rainfall in November and December (mm)	RRnd
Rainfall during the ripening period. (mm)	RRrip
Rainfall during the vegetative cycle (mm)	RRc
Rainfall during the month before harvest (mm)	RRmbh
Number of days of ripening	Ndrip
Yield ($kg \cdot ha^{-1}$)	Y
Berry weight (g)	BW
Bunch rot (% yield)	%ig
Total acidity ($g\ S0_4H_2 \cdot L^{-1}$)	TA
Sugar content ($g \cdot L^{-1}$)	SS

(PC2) contributed 19.1 %. Load vectors integrating the PCA were associated to each other on different scales, forming three groups of years that were characterized according to the variable means of the analyzed period and contributing differently to each PC. Identified groups included a comparable number of years (eight, eight and seven). Group 1 was associated with precipitation vectors. In the eight years rainfall of the vegetative cycle (September - February, RRC) was 20 % higher than average; in seven out of eight years rainfall during maturation (January - February, Rrip) was 55 % higher; and in five out of eight years rainfall on the month before to harvest (Rmbh) doubled the historical average. In six out of eight years, average maximum temperatures during the maturation period (jxT and fxT) were 0.4 °C lower than average. Group 2 was associated to vectors that determined thermal conditions during maturation (jxT and fxT). In the eight years the warmest month temperature (jxT) was on average 1.0 °C higher than the historical average, in seven out of eight years the temperature of the month before harvest (fxT) was higher by 1.2 °C and there were nine more days with temperatures above 30 °C (ND30) than the groups' average. Rainfall was inferior to the historical average. During the vegetative cycle (RRC) in seven out of eight years it was lower than the average in 131 mm to 333 mm. During pre-veraison (RRso, RRnd) in seven out of eight years it was lower than average in 68.7 % and during maturation (Rrip), it was lower in 48.1 % in the eight years (Tab. 2). In the month before harvest (Rmbh) rainfall was 50 % of the expected in seven out of eight years. Group 3 was associated to fresh thermal conditions during maturation. Average temperature of January and February (jxT and fxT) were 1.0 °C lower than the historical average and night temperature the month before harvest (fNT) was 0.83 °C lower than the average. Days with temperatures above 30 °C (ND30) were 12.3 days lower than the average. Rainfall was higher than average during the budbreak-fruit set period (RRso, RRnd) and in the month before harvest, it was 47.5 % lower than average (Rmbh) in five out of seven years (Tab. 2). The DCA confirms the three groups of years of the PCA. DCA analysis showed that the first two principal canonical axes explained 97.3 % of the total variance (Fig. 2). The canonical axis 1 (DC1) contributed 72.3 % and the climate variables that most contributed to the discrimination of the groups were RRmbh, GDDrip and fXT. The canonical axis 2 (DC2) contributed 24.5 % and the functions that most contribute to the discrimination were precipitations in the different stages of the crop cycle (RRC, RRso, RRrip).

Plant response and grape composition. Group of years: Group 1 recorded higher yields and bunch rot percentages ($p = 0.049$, $p = 0.0001$ respectively), as well as the longest ripening period ($p = 0.0012$), which was extended fourteen and nine more days in relation to groups of years 2 and 3 respectively. Total acidity was higher ($p = 0.0006$) and sugar content was the lowest ($p < 0.0001$). Sugar content was 10 $g \cdot L^{-1}$ and 36 $g \cdot L^{-1}$ lower, regarding groups 2 and 3 respectively. In six out of eight years that form this group, alcohol content required to achieve Preferential Quality Wines was not met (PQW, minimum alcohol required 12.1 ° INAVI, http://www.inavi.com. uy/). Group 2, presented the lowest berry weight and bunch rot percentage as well as the shortest maturity period. In six out of eight years, acidity was the lowest compared to years of groups 1 and 3 and alcohol content required for PQW category was not achieved. Group 3, had 20 % and 15 % lower yield (regarding group 1 and 2 respectively), the highest berry weight, and an intermediate acidity value in relation to the other two groups. Sugar contents were higher and during the seven years alcohol content required for PQW category was reached and exceeded (Tab. 2).

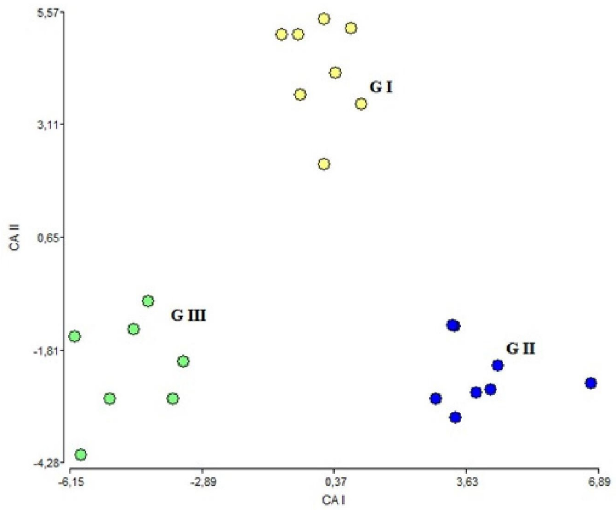

Fig. 2: Lineal discriminant analyses. Group I (GI): high bunch rot and high acidity, Group II (GII): low acidity and low sugar and Group III (G III): High sugar and low yields.

Correlations between thermal and water variables with plant response and grape composition: Yield was positively correlated with precipitations during the cycle (RRc) in the actual season (season ($r = 0.44$, $p = 0.07$) and in the previous one ($r = 0.49$, $p = 0.04$). Berry weight correlated positively with rainfall of the stage before veraison ($r = 0.54$, $p = 0.01$) and negatively with the maximum temperature of February (when berries are not quite ripe) and number of days with temperatures above 30 °C during maturation (fxT, $r = -0.42$, $p = 0.04$, ND30 $r = -0.46$, $p = 0.02$). Bunch rot incidence (%ig) correlated positively with rainfall of the month before

Table 2

Average weather conditions of the years included in each group identified by the PCA. References are in Tab. 1

Group	Yield	Berry weight	Bunch rots	Number of days of ripening	Total acidity	Sugar
I	22700 ± 2435 A	1.67 ± 0,14 A	44.5 ± 23.6 A	78.4 ± 9.8 A	5.6 ± 0,62 A	195 ± 12.5 A
II	21430 ± 4278 AB	1.57 ± 0, 21 A	6.7 ± 7.1 B	69.3 ± 9.7 B	4.2 ± 0,58 C	205 ± 15.1 B
III	18200 ± 3933 B	1.71± 0,17 A	9.3 ± 8,8 B	63.2 ± 7.8 B	4.9 ± 0,92 B	231± 15.8 B

Table 3

Mean values for the major variables of each group identified by the PCA (Yield in kg·ha^{-1}, Berry weight in g, Bunch rots in % of yield, Number of days of ripening, Total acidity in g of $S0_4H_2$·L^{-1} and Sugar in g·L^{-1}). Differences between the variables of the years of each group according to the Fisher test (p <0.05)

	Group I (wet and template in maturation)	Group II (dry and warm)	Group III (fresh, wet in spring and dry in maturation)	Historical weather average
jXT (°C)	29.11	30.20	27.38	29.2
fXT (°C)	27.03	28.90	26.98	27.2
fNT (°C)	16.79	16.89	16.07	16.9
GDDrip (°C)	822.5	903.1	827.9	852.4
dGDD (°C)	12.20	12.81	11.66	12.25
ND30nh	37.50	46.14	27.0	37.20
RRso (mm)	217.3	123.6	237.9	191.8
RRnd (mm)	150.1	101.1	302.7	196.9
RRrip (mm)	395.8	132.4	204.1	254.9
RRc (mm)	773.1	427.0	754.7	643.7
RRmbh (mm)	195.7	62.8	71.7	98.8

harvest (RRmbh, r = 0.89, p < 0.0001), of the maturation period (Rrip, r = 0.70, p = 0.0002) and of the vegetative cycle (RRc, r = 0.45, p = 0.03) and negatively with berry sugars content (SS, r = -0.40, p = 0.05). The duration of the maturation period was determined by the minimum temperature of the month before harvest and the daily sum of temperature during this period. Grape acid content had a negative effect on the harvest date (fNT, r = 0.67, p = 0.0005, dGDD, r = 0.53, p = 0.009, TA, r = -0.53, p = 0.009).

Grape composition was associated with rainfall and temperature. Crop cycle and ripening period rainfall correlated positively with acidity (RRc, r = 0.47, p = 0.02 and Rrip, r = 0.43, p = 0.03 respectively), whereas rainfall of the month before harvest, correlated negatively with berry sugars content (RRmbh r = -0.46, p = 0.02). During maturation period, correlations were negative between temperatures and acidity (jxT, r = -0.53, p = 0.0092, fxT, r = -0.35, p = 0.10) and with daily temperature accumulation (dGDD r = -0.60, p = 0.002).

Through stepwise multiple regression analysis it was possible to determine the variables of more weight in each group (Tab. 4). Group 1 presented the highest bunch rot. The incidence of bunch rot was positively related to the maximum temperatures of the month prior to harvest (fXT), as well as RRrip and Y (r^2 = 0.99, p = 0.003). Group 2 was identified with the composition of the grape. Acidity was positively conditioned by yield (Y), and negatively with temperatures higher than 30 °C from November to January (ND30nh) and with daily degrees during the ripening period (dGDD) (r^2 = 0.97, p = 0.0003). The sugar concentration was modeled according to climatic variables and yield. For this group, yield, thermal accumulation (dGDD, GDDrip), and precipitation in the ripening period (RRrip) negatively affected their concentration (r^2 = 0.96, p = 0.016).

In group 3 the model yield was explained by the Accumulated radiation from budburst to fruit set in the precedent year (ARbd-fsA-1) and negatively with the maximum mean temperature of the month prior to harvest (fXT) (r^2 = 0.86, p = 0.01).

Discussion

During the studied period, climatic variability reflected in the grouping of years according to meteorological conditions determined yield, grape composition and its sanitary status, as Leeuwen *et al.* (2004) indicated as well as Fourment *et al.* (2018) for the study region. Grape oenological quality depended on the years conditions, which will result in different wine categories and therefore different price, in

Table 4

Multiple regression analysis for the variables that explain the group I, II and III by a step-wise selection with p-value of retention of 0.10. References are in Tab. 1

Group	Response variable	Model	R^2	p-value
I	% Yield	302.13+7.89(jXT)+0.22(RRrip)+0.0003(Y)	0.99	0.003
	TA	9.01+4.5x10^{-3}(GDDrip)-0.32(fXT)+ 0.03(ND30nh)	0.98	0.0008
II	TA	50.35 + 1.9 x 10^{-4}(Y)-0.08(ND30nh)-2.99(gGDD)	0.97	0.0003
	SST	1830.3-0.01(Y)-101.6(dGDD)-0.09 (GDDrip)-0.77(RRrip)	0.96	0.016
III	SS	221.27- 0.16(RRnd)+2.4x10^{-3}(Y)+0.10 (RRrip)	0.99	0.0001
	Y	-97803+1.41(ARb-fsetA-1)-2269 (TMF)	0.86	0.01
	BW	-3.30+ 1.4 x 10 $^{-3}$(RRndA-1) +0.31(Tmf)+6.9 x 10^{-4} (GDDrip)	0.98	0.001

accordance with Ashenfelter (2008). The climate variables that most condition the plant's response are deficit and excess rainfall (as shown by the discriminant), particularly those that occur during ripening. Years with excess water (group 1) will be characterized by greater acidity and a greater incidence of rotting. On the contrary, years with water deficit will be characterized by low acidity and lower sugar contents.

Group 1, which was characterized by abundant rainfall years and temperatures lower than the historical average during maturation stage, generated conditions in which, according to the found correlations, sanitary status was poor, must acidity high, sugars content low and ripening period was the longest; in agreement with Hunter and Bonnardot (2011) and González-Domínguez *et al.* (2015). Sugars and acids presented a thermal-dependent metabolism, while rainfall and low temperatures (characteristic of temperate and humid climates), were associated with higher musts acidity and sugars dilution (Jackson and Lombard 1993, Greer and Weston 2010, Sadras *et al.* 2013, Greer and Weedon 2014). These climate conditions occurred in this group of years, resulted in a slower acidity degradation *via* malic acid and sugars accumulation/dilution, resulting in an extended maturation period and later harvests, since harvest decision was taken based on total acidity and sugars content evolution. These same conditions, particularly in the month before harvest, favoring bunch rot development (Ferrer *et al*. 2011, Steel *et al*. 2013). Another consequence of humid conditions during ripening are plant vigor increase, estimated by pruning weight (data not shown), which in general is associated with higher yields, negative effects on sanitary status and grape composition (Valdés-Gómez *et al.* 2008, Filippetti *et al.* 2013). Wines made from these musts, will be of lower commercial category, with color defects and a short period of conservation due mainly to the presence of bunch rot in grapes (Steel *et al*. 2013). Group 2 was characterized by rainfall deficiency and high temperatures, conditions which according to the correlations found, had the smallest berries as a result; good sanitary status; sugars and acidity contents lower than average; and as expected, early harvests, in accordance with several authors (Webb *et al*. 2008, Greer and Weston 2010, Sadras *et al*. 2013, Martínez de Toda *et al*. 2019). The low acid content of the years of this group corresponds to malic acid degradation as a consequence of high temperatures during maturation, which in 72 % of the days exceeded 30 °C. On the other hand, these conditions also negatively influence the photosynthesis process and berry sugars accumulation, according to the authors who showed that temperatures above 25-30 °C may limit photosynthesis (Greer and Weston 2010, Greer and Weedon 2014). Water stress conditions are reported as a cause of photosynthesis blockage (Bota *et al.* 2004). In this group, rainfall was deficient in the different crop stages, which generated a negative water balance. For example, in 2016, it corresponded to a Drought Severity Index (-177 mm) when the climate of the region lists this Index in the Moderate Drought range, with historical values of 50 mm (Ferrer *et al.* 2007). Water deficit during the bud induction period caused a lower yield in the following year without considering the weather conditions during this year. That is the case in 5 of the 8 years (29,660 kg·ha^{-1} to 19,400 kg·ha^{-1}, from 19,400 kg·ha^{-1} to 15,100 kg·ha^{-1}, from 18,400 kg·ha^{-1} to 16,900 kg·ha^{-1}, from 19,100 kg·ha^{-1} to 17,200 kg·ha^{-1}, from 26,400 kg·ha^{-1} to 22,100 kg·ha^{-1}, for year 1, with water deficit, and year 2, respectively), in agreement with that reported by Guilpart *et al.* (2014) and Mendez-Costabel *et al.* (2014). Low berry weight can be attributed to the joint effect of water deficit in pre-veraison and to high temperatures during maturation period, according to the correlations found, and to what was reported by Ojeda *et al*. (2001), Greer and Weston (2010) and Ferrer *et al*. (2014). These conditions also ensured healthy grapes (Steel *et al*. 2013). Must acidity was below the expected for this variety, which can cause wines with conservation and stability problems as well as deficient organoleptic characteristics (Jaxkson and Lombard 1993).

Group 3, which was characterized by temperate thermal conditions, no water restrictions in the first stage of the crop cycle and moderate water deficits in the maturation period, resulted in the conditions for great sugar and anthocyanin accumulation. The lower average water component in the budbreak-fruit set period, allowed a good leaf surface installation that favored photosynthates production, which together with low rainfall in the month before harvest caused the highest sugar content in this group compared with the groups of years 1 and 2 (Escalona *et al*. 2003, Kliewer and Dkoozlian 2005). On the other hand, rainfall in this period and the yield per hectare below average, according to the correlations established, positively influenced berry size and following year yields, as highlighted in the aforementioned paragraph. In this group of years, the maturation period lasted as long as the average of the variety (Fourment *et al.* 2013). The climate conditions in the month before harvest of lower rainfall and cool daily and nocturnal temperatures favored the healthy status. Thermal conditions prevented dehydration in the berry growth final stage, which contributed, along with water supply in pre-veraison, to its larger size (Ojeda *et al*. 2001, Rogiers *et al*. 2004). In several years of this group, anthocyanin content was higher in response to cool night temperatures and moderate water deficit during maturation period, according to what was reported by Mori *et al*. (2005) and Ferrer *et al.* (2014). From the oenological point of view this group of years was the one which obtained the best vintages, since the grape composition had the highest sugar contents, extractable anthocyanins and phenolic richness which makes them premium wines (Gonzalez-Neves *et al.* 2004, Fourment *et al.* 2018).

Conclusions

For the studied years, climatic variability was highly significant and grapevine response (represented by 'Tannat' variety) was influenced by this variability. The month prior to harvest was the most sensible period of the sanitary state, yield and of grape composition, subject to water and thermal regime. In interaction with the climate, the level of yield of the plant influences the health and composition of the grape. Given that meteorological conditions of the year have a strong influence on grape oenological quality and wine rating, new studies should be carried out regarding the effect of different climate components and their interannual variability, especially the influence of ENSO events on this perennial crop.

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