

# Tannat grape composition responses to spatial variability of temperature in an Uruguay's coastal wine region

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**Abstract** Spatial variability of temperature was studied in relation to the berry basic composition and secondary compounds of the Tannat cultivar at harvest from vineyards located in Canelones and Montevideo, the most important wine region of Uruguay. Monitoring of berries and recording of temperature were performed in 10 commercial vineyards of Tannat situated in the southern coastal wine region of the country for three vintages (2012, 2013, and 2014). Results from a multivariate correlation analysis between berry composition and temperature over the three vintages showed that (1) Tannat responses to spatial variability of temperature were different over the vintages, (2) correlations between secondary metabolites and temperature were higher than those between primary metabolites, and (3) correlation values between berry composition and climate variables increased when ripening occurred under dry conditions (below average rainfall). For a particular studied vintage (2013), temperatures explained 82.5% of the spatial variability of the berry composition. Daily thermal amplitude was found to be the most important spatial mode of variability with lower values recorded at plots nearest to the sea and more exposed to La Plata River. The highest levels in secondary compounds were found in berries issued from plots situated as far as 18.3 km from La Plata River. The increasing

knowledge of temperature spatial variability and its impact on grape berry composition contributes to providing possible issues to adapt grapevine to climate change.

**Keywords** Berry composition · Mesoclimate · Tannat · Temperature variability · Grapevine

## Introduction

Increase in issues related to grapevine adaptability to climate change involves the development of the understanding of local environmental factors and their impacts on grapevine physiological functioning as well as berry and wine composition.

Bioclimatic indices adapted to viticulture, such as the heat accumulation of Winkler (Winkler et al. 1974) or Huglin (1978) or the climate-maturity groupings of Jones et al. (2010), have been used in various studies to assess the climatic potential for viticulture at macroscales (Tonietto and Carbonneau 2004; Anderson et al. 2012) or to assess the impact to climate change in wine regions (Quéno 2014). At the scale of a wine region (mesoclimate), climate is affected by topography (Bonney et al. 2013; Madelin et al. 2014) and/or distances from rivers (Blanco-Ward et al. 2007; Hall and Jones 2010). Proximity to large water bodies (sea or lake) also affects the climate of coastal wine regions. The physical contrast between sea/lake and land generates local air circulations that affect the climatic conditions of the surrounding regions as it was shown for the coastal wine region of South Africa (Bonnardot et al. 2005).

In Uruguay, the climate suitability for viticulture was investigated using bioclimatic indices and resulted in the macroclimate zoning of wine regions (Ferrer et al. 2007). In the southern coastal wine region, the impact of La Plata River breeze penetration on temperature over the Canelones and

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Montevideo districts was analyzed (Fourment et al. 2014). However, the temperature effect on grapevine physiological functioning and hence final grape composition that ultimately affect wine characteristics remains unknown in the country.

Regarding mesoscale interactions between temperature and grapevine functioning, occurrences of extreme climate conditions and grapevine responses to them are of importance for quality of the wine. Occurrences of extreme climate events such as frost in spring and heat waves during summer (Bonnefoy et al. 2013; Fourment et al. 2014) in vineyards revealed significant temperature variability between plots within a region. Studies combining climate and grapevine response showed advanced phenological stages under hot situations (Bonnefoy et al. 2013) and a diversity of responses of grape berry composition and wine (Nicholas et al. 2011; Barnuud et al. 2014).

The direct or indirect responses of primary and secondary berry metabolites to temperature are known (Sadras et al. 2012; Bonada and Sadras 2015). High (daytime and nighttime) temperatures during the ripening period cause high sugar accumulation and degradation of acid contents (Kliwer 1973), due to a consumption of malic acid (Jackson and Lombard 1993), and alter polyphenol synthesis (Mori et al. 2007; Nicholas et al. 2011). Thermal stress during ripening period causes degradation and inhibition of anthocyanin accumulation (Mori et al. 2007). Nevertheless, Sadras et al. (2012) reported that the grape berry composition is a result of the interaction within the soil-plant-atmosphere system.

Vineyards of southern Uruguay are characterized by gentle topographical features bordered by La Plata River estuary (Fourment et al. 2014). In this country, Tannat is considered as the best-suited grapevine variety to the local environmental conditions. This is the most cultivated variety, representing 25% of the total vineyard surface and 26.5% of the national wine production (INAVI 2015). Tannat is characterized by a high oenological potential due to high-level contents of anthocyanins, tannins, and acidity (González-Néves et al. 2010) producing wines with strong originality and typicity.

The study focuses on Tannat's response to temperature spatial variability at mesoscale in terms of the grape berry composition in the southern coastal wine region of Uruguay, in order to increase knowledge that could be of benefit to the Uruguayan wine industry.

## Materials and methods

### Site description

The study was carried out in the southern coastal wine region of Uruguay in the Canelones and Montevideo districts, which represent 76.1% of the total vineyard surface of the country (INAVI 2015) (Fig. 1). The climate was classified as warm

temperate, with temperate nights and moderated drought, corresponding to the  $IS_{A1}HI_{A4}CNI_{A2}$  climatic group, according to the “Multicriteria Climatic Classification” method for vineyards (Tonietto and Carbonneau 2004; Ferrer et al. 2007).

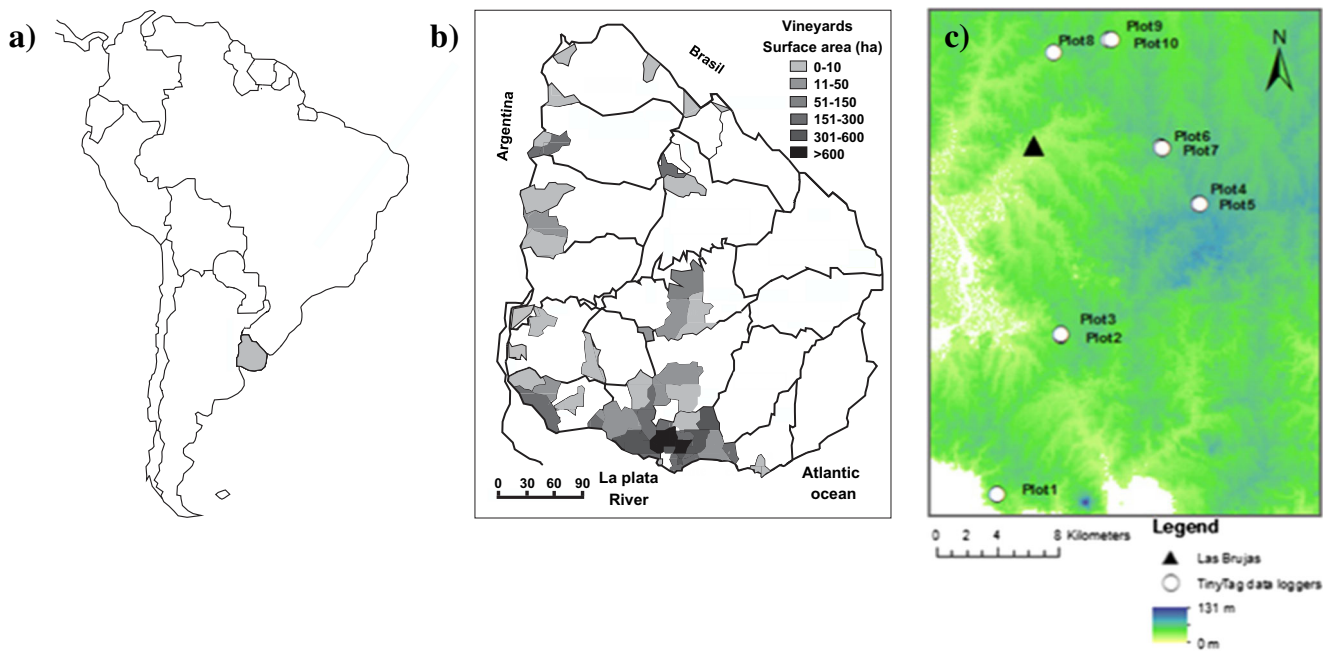
A network of 10 experimental plots was selected in five commercial vineyards of Tannat. These vineyards were chosen in order to investigate the influence of the La Plata River, soils, and topography. In four cases, two contiguous plots were selected (plots 2 and 3, plots 4 and 5, plots 6 and 7, and finally plots 9 and 10), yet at different elevations and heterogeneous soil properties (depth, temperature, water-holding capacity) in order to assess how various environmental factors at the plot scale may lead to significant differences in local temperature and berry composition (Table 1). Also, it was used to minimize the winegrower management effect. At all plots, the training system was the vertical shoot position (VSP), and canopy was managed for producing quality red wine. However, five winegrowers were involved, and thus, grapevine management may have differed.

### Climate data and analyses

Mesoclimate and grapevine data were analyzed over three growing seasons: 2011–2012, 2012–2013, and 2013–2014 corresponding to the 2012, 2013, and 2014 vintages, respectively. It starts from September year  $N^{-1}$  to March year  $N$  including grapevine growth from September to December approximately and berry ripening as from January onwards.

Daily maximum and minimum temperature and rainfall from INIA Las Brujas conventional station (INIA 2015) were used to analyze the climatic conditions of the three studied seasons compared to the 1972–2015 long-term average.

Hourly temperature data for the three growing seasons were obtained from 10 “TinyTag Talk 2” thermal sensors (Gemini Data Loggers Ltd., UK) installed in the selected commercial vineyards and situated in the training system at 1.5 m above the ground. Different climatic scales were used to characterize viticultural areas (Asselin et al. 2001) and bioclimatic indices to define the aptitudes of a region in terms of grape and wine production (Winkler et al. 1974; Tonietto 1999). Calculation of daily and monthly data (minimum and maximum temperature) as well as bioclimatic indices for the three growing seasons was used in order to assess temperature spatial and seasonal variation in the vineyards. The growing degree day (GDD) is the summation of temperature units above a base temperature of 10 °C ( $GDD = \sum(T_{mean} - 10)$ ) (Winkler et al. 1974). The heliothermic or Huglin index (HI) (Huglin 1978) is, as in the case of GDD, based on a summation of heat units above 10 °C. It was calculated using the daily mean and maximum temperatures from 1 September to 28 February ( $HI = \sum(T_{mean} - 10 + T_{max} - 10) / 2 \times k$ ). The  $k$  coefficient expresses the day length in relation with latitude (for Uruguay is equal to 1). February mean minimum temperature was used to characterize nighttime climatic



**Fig. 1** Location of the studied area at the scale of **a** South America, **b** Uruguayan wine-producing regions, and **c** Montevideo and Canelones wine districts with location of local data loggers and the automatic meteorological station of INIA Las Brujas (map source: ArcGIS)

conditions during the ripening period. This corresponds to the “cool night index” (CNI) (Tonietto and Carbonneau 2004) adapted for Uruguay (Ferrer et al. 2007).

Mean maximum and minimum temperatures of January and February from the TinyTag Talk 2 sensors were used to assess its spatial variability at fine scale during ripening of grapevine. The calculation of the number of days and hours with temperature above 30 °C (ND30; NH30) and 35 °C (ND35; NH35), which represent thermal thresholds for grapevine physiological functioning (Hunter and Bonnardot 2011), was calculated during January, February, to middle March (vintage generally take place in March). The diurnal cycle of temperature of the warmest day

of the study period (15 February 2012) was used to study temperature variability at fine scale under hot conditions for viticulture (i.e., >30 °C) with the aim of identifying the potential effect of La Plata River on temperature in the vineyards.

**Berry samples and analyses**

Berry samples were collected at harvest using the method suggested by Carbonneau et al. (1991). For each plot, two double samples of 250 berries were collected from 30 plants within two rows in each vineyard. Grape berry composition including sugar concentration (g/l) by refractometry, titratable

**Table 1** Geographical characteristics of the 10-plot network: commercial vineyard (letters A to E represent five owners), shortest straight line distance from La Plata River (in km), altitude (meters above sea level), slope (%), aspect and location, as well as for the automatic climatic station of INIA Las Brujas

Plots	Commercial vineyard	La Plata River distance (km)	Altitude (m a.s.l.)	Slope (%)	Aspect	Latitude	Longitude
Plot 1	A	0.9	34	3.3	South	34° 53' S	56° 19' W
Plot 2	B	11.7	31	1.3	West	34° 47' S	56° 16' W
Plot 3	B	11.7	29	0.9	West	34° 47' S	56° 16' W
Plot 4	C	18.3	95	2.3	East	34° 42' S	56° 10' W
Plot 5	C	18.3	83	2.9	East		
Plot 6	D	21.9	65	2.6	Southeast	34° 42' S	56° 10' W
Plot 7	D	21.9	62	2.6	South	34° 40' S	56° 12' W
Plot 8	D	28.0	53	4.4	Southeast	34° 40' S	56° 12' W
Plot 9	E	28.6	49	1.6	North	34° 37' S	56° 17' W
Plot 10	E	28.6	46	3.6	Southeast	34° 36' S	56° 14' W
INIA Las Brujas Station		18.6	32	3.3	Southwest	34° 40' S	56° 20' W

acidity (g H<sub>2</sub>SO<sub>4</sub>/l) by titration, and pH by potentiometry was analyzed according to the International Organization of Vine and Wine (OIV 1990). Phenolic potential, such as total potential in anthocyanins, the potential in extractable anthocyanins and phenolic richness of grapes, was analyzed according to Glories and Augustin (1993). All the measurements related to phenolic potentials were carried out by duplication with a Shimadzu UV-1240 Mini (Shimadzu, Japan) spectrophotometer. Total and extractable potential in anthocyanins and polyphenol richness are indices that provide value to enology of grape and improve vinification management (González-Néves et al. 2010).

### Statistical analyses

A univariate procedure (ANOVA) was used to determine significant differences in climate data and berry composition between plots (Tukey grouping;  $\alpha = 5\%$ ). The multivariate method of principal component analysis (PCA) was performed to determine significant correlations between temperature and berry composition variables over the region. PCA analyses were used to demonstrate relationships between data obtained over the three studied seasons and separately within each season to identify a possible vintage effect. Using highly correlated variables from the PCA ( $r > 0.6$ ), a cluster analysis was performed to group plots of similar profiles. Differences in berry composition were also georeferenced by ArcGIS map source with the results of the Tukey grouping.

## Results

### Seasonal climate variability

The grapevine growing season in Uruguay begins in September and finishes in middle of March. On average for the 1972–2015 long-term period, bioclimatic indices at INIA Las Brujas reach a value of 1651 and 2207 for GDD and HI, respectively. Considering the vintages of 2012, 2013, and 2014, no statistical differences were found in heat accumulation at the end of the growing season between these vintages. However, these indices were above long-term average of 1972–2015, being 2013 the warmest growing season (+100 units GDD) (results not shown).

Looking at the ripening period, the 2012 vintage was the warmest of the three studied growing seasons with maximum temperatures 1.2 and 1.3 °C above the long-term average in January and February, respectively, and February minimum temperature 1.5 °C above average (Table 2). In opposition, the 2014 ripening period was cooler, especially in February with maximum temperature 1.6 °C below average and particularly wet. Thus, the main climatic characteristic of the 2014 ripening period was its large amount of rainfall with a total of

469 mm, i.e., twice more than the long-term average and around 300 mm more than the other two vintages. The particularity of the 2013 ripening period compared to the other two lied in drier conditions, nearly 80 mm less than the long-term average and 330 mm less than the 2014 ripening period. Despite being the warmest growing season of the three studied seasons, thermal conditions during the 2013 ripening period were close to the long-term average in terms of maximum temperature and slightly cooler at night (February minimum temperature of about 0.5 °C below average).

### Spatial variability of temperature

Considering bioclimatic indices, some statistical differences between plots were found (Table 3). Indeed, plot 5 appeared to be the coolest in terms of heat accumulation expressed in GDD and HI ( $R^2 = 0.81$ ;  $P = 0.0001$  and  $R^2 = 0.95$ ;  $P < 0.0001$ , respectively). The GDD mean value for plot 5 was 1648, while it reached more than 1750 units for plots 1, 2, 3, 8, 9, and 10. Thus, the greatest spatial difference in terms of GDD was of 156 units on average between plot 1 (the warmest plot) and plot 5 (the coolest plot), reaching 162 units during the warm growing season of 2012–2013. Considering the HI, the greatest difference was obtained between plot 9 and plot 5 (212 units on average), reaching 231 units using the data of 2012–2013. The difference between the seasons was on average of 53 units of GDD and 19.6 units of HI. The seasonal difference reached only 70 units in terms of GDD at plot 9 (28.6 km inland) and 36 units in terms of HI at plot 6 (21.9 km inland) between the warmest season (2012–2013) and the coolest season (2011–2012). Hence, the differences between plots were greater than the differences between seasons.

Considering the CNI results, no statistical differences between plots were found (Table 3). The CNI ranged between 16 and 18 °C on average over the three vintages with plot 1 experiencing the warmest and plot 6 the coolest night conditions during February. Plots 1 and 4 reached 19.5 and 18 °C in February 2012 and experienced warm nights (>18 °C), while in February 2013, all plots, except plot 1, experienced cool night conditions (<16 °C).

The difference in thermal stress between plots, which is of fundamental importance for the development of berry aromas and color, was assessed using ND35 and NH35. Results showed significant differences between plots (Table 4). Plots 8 and 9 experienced 8 days on average with a maximum ND35 leading to a total of 25.7 and 27 h of thermal stress for the grapevine, respectively, while plot 1 experienced 2 days and 7 h of extreme thermal conditions only. Due to its proximity to the La Plata River, plot 1 had a smaller daily thermal amplitude with the warmest night conditions (Table 3) and the lowest thermal stress during the day (Table 4).

Despite the relative flat terrain of the study area, the highest elevation being 95 m (plot 4), the diurnal cycle of temperature



**Table 2** Mean maximum (MaxT) and minimum (MinT) temperature (°C) and rainfall (R in mm) during the ripening period of 2012, 2013, and 2014 in comparison to the 1972–2015 long-term average at Las Brujas weather station (INIA 2015)

	MaxT (°C)				MinT (°C)				R (mm)			
	2012	2013	2014	1972–2015	2012	2013	2014	1972–2015	2012	2013	2014	1972–2015
January	30.3	29.2	28.9	29.1	16.6	16.4	17.8	16.8	60.7	50.3	281.2	106.3
February	29.3	27.8	26.4	28.0	18.2	16.2	17.6	16.7	109.7	88.9	187.4	116.7
Total									170.4	139.2	468.6	223.0

Note that February mean minimum temperature corresponds to the cool night index (CNI)

between two contiguous plots shows important differences which may be of relevance for grapevine, particularly during a specific hot situation for viticulture. In order to illustrate the spatial variability of temperature over short distances, Fig. 2 shows the hourly temperature for 15 February 2012 in the 10 studied plots. Maximum temperatures for this particular day reached 31.9 °C at plot 1, 36.3 °C at plot 6, and 38.9 °C at plot 7. While the plot under the moderating influence of the La Plata River (plot 1) experienced temperatures below 32 °C, the others recorded between 2 and 6 h with temperature above 35 °C, respectively, during which grapevine may have experienced extreme thermal stress.

### Tannat grape berry composition at harvest

In 2012, grapes were harvested late in 5 days (between 2 and 7 March). In 2013, harvest took place early (between 19 and 28 February), and in 2014, it took 16 days to

harvest the grapes (between 18 February and 6 March). Grape health status and berry composition were different for these three vintages. Because of rainfall close to harvest at some places and consequently *Botrytis* spp. Infections, there was a decrease in yield (plots 1, 9, and 10) in 2012. In 2014, the large amount of rainfall during summer in the entire region caused several infections of *Botrytis* spp. in the berries, causing different levels of incidence within all plots.

The averages for the compounds showed that plot 1 was the most variable under those three vintages, in terms of sugar content (SC), acidity (TA), and polyphenols (potential in extractable anthocyanins (Aph3.2) and phenol richness (A280)), while the plots with balanced composition for red wine elaboration were plots 2, 4, 5, and 6 with the highest values in SC ( $R^2 = 0.62$ ;  $P < 0.0001$ ), Aph3.2 ( $R^2 = 0.35$ ;  $P = 0.0008$ ), and A280 ( $R^2 = 0.34$ ;  $P < 0.01$ ) and lowest TA ( $R^2 = 0.77$ ;  $P < 0.0001$ ) (Fig. 3). In the same

**Table 3** Bioclimatic indices: growing degree days (GDD), Huglin index (HI), and cool night index (CNI) calculated at the local scale (plots) for three seasons (2012, 2013, and 2014) and average for the three seasons (mean in column) and 10 plots (mean in row)

Plot	GDD*				HI**				CNI			
	2012	2013	2014	Mean	2012	2013	2014	Mean	2012	2013	2014	Mean
Plot 1	1776	1829	1804	1803	2327	2351	2328	2335	19.5	17.6	18.8	18.6
Plot 2	1729	1757	1757	1748	2400	2400	2367	2389	17.9	16.0	17.4	17.1
Plot 3	— <sup>a</sup>	1767	1748	1758	— <sup>a</sup>	2412	2366	2389	17.4	15.8	17.4	16.9
Plot 4	1692	1741	— <sup>b</sup>	1717	2344	2366	— <sup>b</sup>	2355	18.0	15.8	— <sup>b</sup>	16.9 <sup>c</sup>
Plot 5	1617	1667	1659	1648	2260	2267	2261	2263	17.6	15.5	17.0	16.7
Plot 6	1671	1733	1727	1710	2325	2361	2344	2343	17.9	15.7	14.0	15.9
Plot 7	1649	1693	1710	1684	2341	2365	2355	2354	17.2	15.0	16.7	16.3
Plot 8	1759	1822	1802	1794	2451	2464	2430	2448	17.8	16.0	17.5	17.1
Plot 9	1743	1813	1796	1784	2474	2498	2452	2475	17.3	15.6	17.3	16.7
Plot 10	1713	1771	1772	1752	2431	2457	2432	2444	17.4	15.4	17.2	16.7
Mean	1705	1759	1753	1740	2373	2394	2363	2380	17.8	15.8	17.0	16.9

<sup>a</sup> The sensor was not installed early enough to calculate the indices

<sup>b</sup> 40% of missing data

<sup>c</sup> Mean of two seasons

\*Statistical differences between plots ( $R^2 = 0.81$ ;  $P < 0.0001$ )

\*\*Statistical differences between plots ( $R^2 = 0.95$ ;  $P < 0.0001$ )

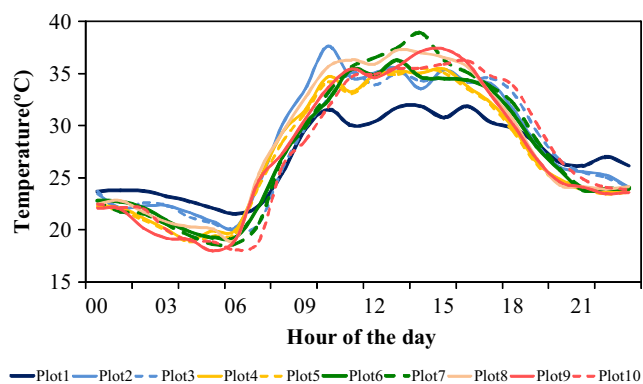
**Table 4** Numbers of days and hours with temperature above 35 °C (ND35 and NH35) between 1 January and 15 March in 2012, 2013, and 2014

Plot	ND35				NH35			
	2012	2013	2014	Mean	2012	2013	2014	Mean
Plot 1	4	0	2	2.0	17	0	5	7.3
Plot 2	13	3	3	6.3	46	4	18	22.7
Plot 3	9	2	5	5.3	35	3	14	17.3
Plot 4	9	4	–	–	26	3	–	–
Plot 5	7	0	2	3.0	23	0	6	9.7
Plot 6	8	0	4	4.0	23	0	14	12.3
Plot 7	13	4	4	7.0	37	5	15	19.0
Plot 8	14	6	4	8.0	48	10	19	25.7
Plot 9	14	5	5	8.0	49	12	20	27.0
Plot 10	12	5	4	7.0	37	15	18	23.3
Mean	10.3	2.9	3.7	5.6	34.1	5.2	14.3	17.9

way, plot 5 was the steadiest in terms of vintage variability (standard deviation values), followed by plots 7 and 8.

Analyses partitioned by year showed that plot 5 was the plot with balanced values, reaching the higher sugar content and lower acidity in the grapes in the three vintages. Plots 8 and 10 showed also lowest values in acidity in 2012, 2013, and 2014. In terms of secondary metabolites, plots 2 and 3 showed the highest values in ApH1 (in 2012 and 2014), and plots 3 and 4 reached the highest values in A280 all the years.

Spatial and seasonal variability of grape berry composition is displayed in Fig. 4. Among the composition parameters, SC and ApH3.2 were analyzed due to their greater spatial and temporal variability. Plots situated between 18 and 22 km inland showed the highest values for SC and ApH3.2 (in red, Fig. 4). For those plots, SC reached at least 211 g/l (the poorest value measured in 2014) and ApH3.2 reached 941 mg/l (the greatest value measured in 2012).



**Fig. 2** Hourly temperatures (°C) for 15 February 2012 in the 10 studied plots

Under the same management practices (within vineyards), ApH3.2 and the other polyphenols indices were more stable than SC, with no statistical differences between contiguous plots.

### Sensitivity of the grape berry composition to temperature

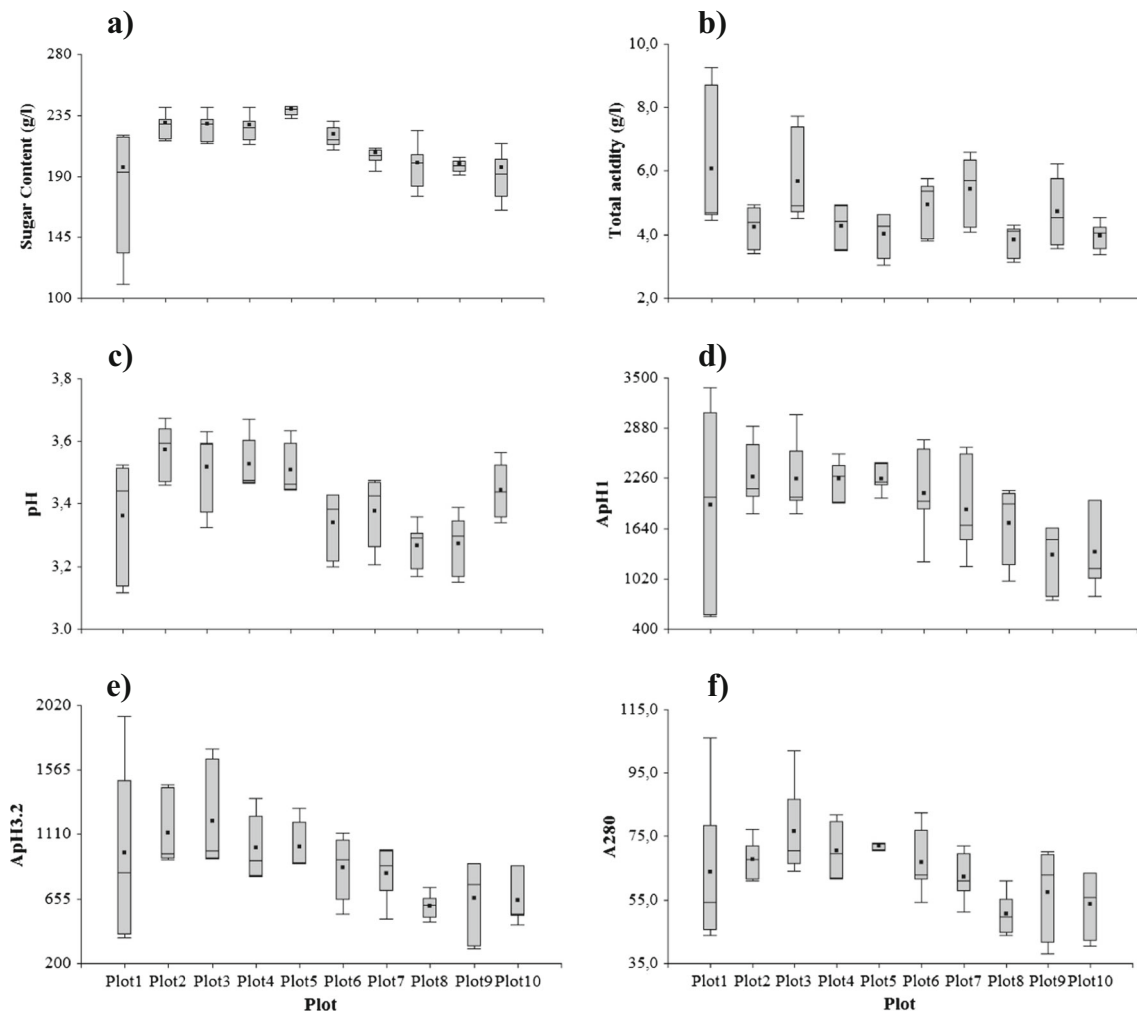
Given the reduced dataset for statistic analyses (three growing seasons), correlations between temperature and berry composition showed weak relationship between variables (Table 5), even if the PCA represented 77.2% of the total variability. Temperature over the growing season was found to be the prevailing indicator for berry composition with significant correlations between the HI and SC ( $r = -0.62$ ,  $P = 0.05$ ), ApH1 ( $r = -0.69$ ,  $P = 0.03$ ), and A280 ( $r = -0.60$ ,  $P = 0.07$ ). Extreme temperature was also a significant indicator for berry composition as shown with correlations between NH35 and secondary metabolites of grape: ApH1 ( $r = -0.58$ ,  $P = 0.08$ ) and A280 ( $r = -0.56$ ,  $P = 0.09$ ). In the PCA of the three vintages, plot 1 was located near the minimum temperatures, while plots 8, 9, and 10 were situated near the maximum temperatures (Fig. 5).

Tannat grape berry composition showed a significant variability that could be associated with temperature when it was analyzed on a yearly basis. PCA performed for the 2013 vintage reached the highest value in total variability (81.6%) in comparison to the 2012 (74.3%) and 2014 (73.4%) vintages. Heat between véraison and harvest (jMaxT, jMinT, TAm, NH30, and NH35) and secondary metabolites in the grape (ApH1, ApH3.2, and A280) were the major contributing variables to component 1 (67.2%). HI, CNI, pH, and TA were the contributing variables to component 2 (14.4%). The climate components on the first principal component were strongly correlated with anthocyanins and phenols (correlations above  $r = 0.70$ ), in a positive way with minimum temperature variables of the ripening period, i.e., night conditions (jMinT and CNI), and in a negative way with maximum temperatures (jMaxT and fMaxT), TAm and NH30. The cluster hierarchical classification using the highest correlated variables from the PCA performed for the three seasons displayed three classes (0.971 of cophenetic correlation coefficient) (Fig. 6). The first cluster was composed of the plot 1, the second one of plots 8, 9, and 10, and the third class of the remaining plots (2 to 7).

## Discussion

### Seasonal climate variability

Although the study was carried out using 3 years of data only (and may not be representative of all situations), two points need to be outlined. (1) The three growing seasons were warmer than the long-term average. This corroborates the warming trend that has been observed in most of wine-



**Fig. 3** Compounds' 3-year average from Tannat grapes at harvest between plots. Sugar content (a). Total acidity (b). pH (c). Total potential in anthocyanins (d). Potential in extractable anthocyanins (e). Phenol richness (f)

growing regions worldwide (Quénoel 2014). (2) The three studied seasons provided contrasted climatic conditions under which spatial variation of temperature and correlation with grapevine data could be investigated.

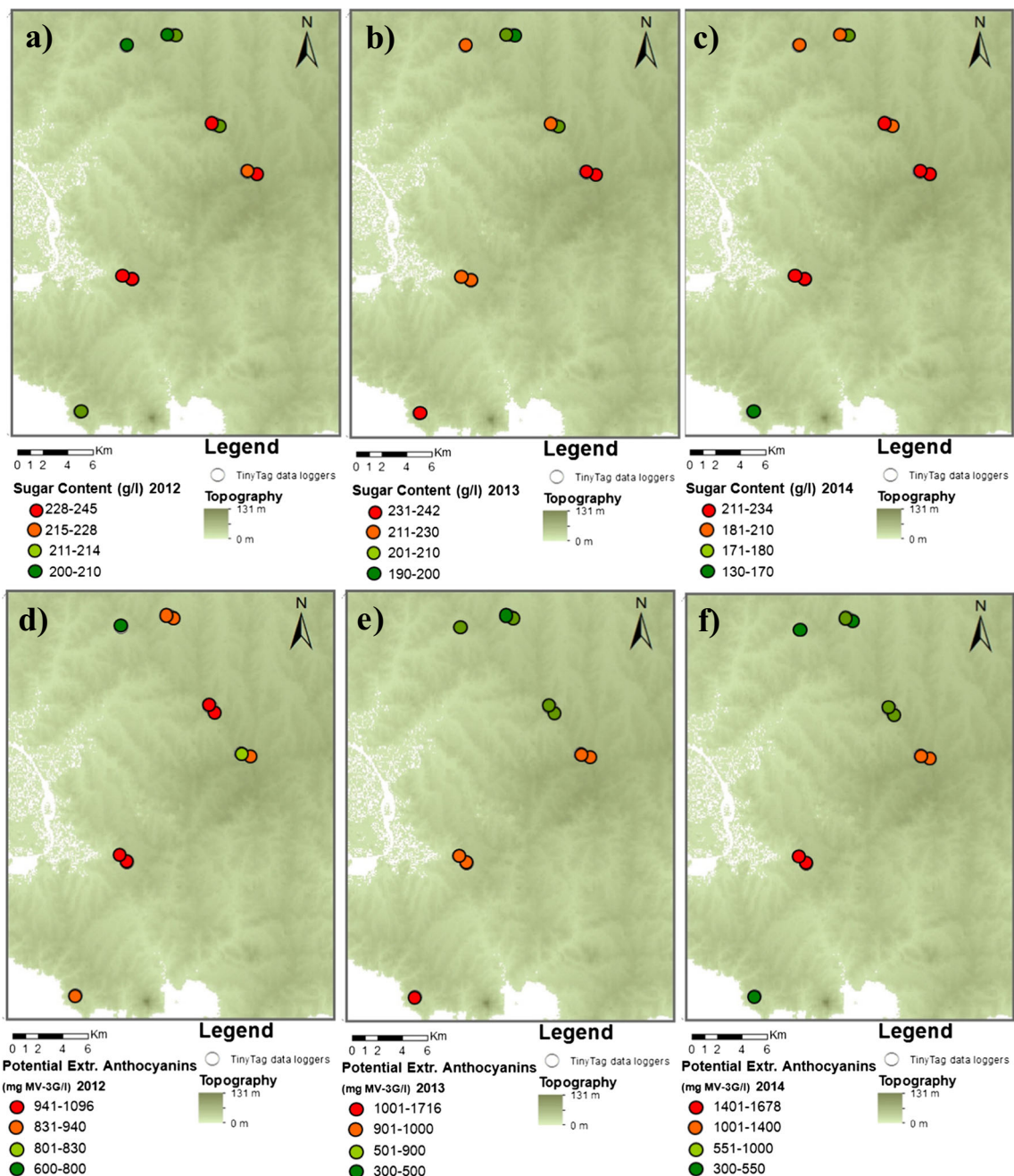
### Climate spatial variation

Results displayed a greater spatial variability of temperatures than temporal variability even in a flat terrain. Similar results were obtained in South Africa (Bonnardot et al. 2005) and France (Bonnefoy et al. 2013).

The results obtained during the ripening period showed a significant spatial variability of temperature over short distances in the region, with a clear La Plata River effect on temperatures. Even if there are differences in the three studied ripening periods, the same features in spatial distribution of temperatures are retrieved. That is crucial in the sense that Barnuud et al. (2014) proved that the ripening period climate is more influential in determining berry composition at maturity than early growing season climate.

Daily thermal amplitude was moderate in plots strongly influenced by the river, such as plots 1, 4, 5, 6, and 7, and was amplified in plots 8, 9, and 10 situated 28 km away from it located near the coast but facing westward, such as plots 2 and 3.

Looking at hourly temperature data and assuming that grapevine experiences high temperature stress above 35 °C (Mori et al. 2007; Hunter and Bonnardot 2011), the diurnal cycle of temperature gave evidence of high differences in potential thermal stress between the plots during the ripening period. There was no thermal stress, or it was considerably reduced in intensity and duration in plots influenced by the river compared to that experienced inland. Even though the sea breeze may reach a distance of 28 km over the wine region under hot situations during summer, Fourment et al. (2014) had documented for the same growing seasons that the influence of the river stopped rapidly 6 km inland (distance difference between plots 7 and 8). Fourment et al. (2014) have also shown that the sea breeze arrival caused a 4.2° drop in temperature between 10:00 and 14:00 local time in vineyards with the south-facing



**Fig. 4** Tannat grape berry composition at harvest in the plots. Sugar content in 2012 (a), 2013 (b), and 2014 (c) and potential in extractable anthocyanins in 2012 (d), 2013 (e), and 2014 (f). Colors display results from the Tukey grouping ( $\alpha = 5\%$ )

plots. That suggests that over hot situations, La Plata River could play an important role of moderating the thermal stress, which is beneficial for grapevine functioning.

However, some locations near the river, such as plots 2 and 3 located at 11.7 km from the coast, are protected from effects of sea breeze of La Plata River due their topography features (narrow basin) and their westward exposure. Comparing to plot 1, they recorded higher maximum temperature and thus greater daily thermal amplitude during ripening period, which may have affected berry composition significantly.

Besides the fact that thermal stress was experienced inland, the duration with extreme temperature (above 35 °C) was three times higher at plot 7 than at plot 6 compared to plot 1 near the river. Although these two sites are situated on a similar slope (2.6%) and 58 m apart only, the differences in altitude displayed topoclimate differences that could have hold implications on grapevine development. Consequently, sugar accumulation, malic acid content, skin color, and phenolic content on berries could have been influenced by these local conditions during grape maturation (Mori et al. 2007).



**Table 5** Correlations and *p* value of the PCA between temperature and Tannat composition at harvest for the three studied vintages

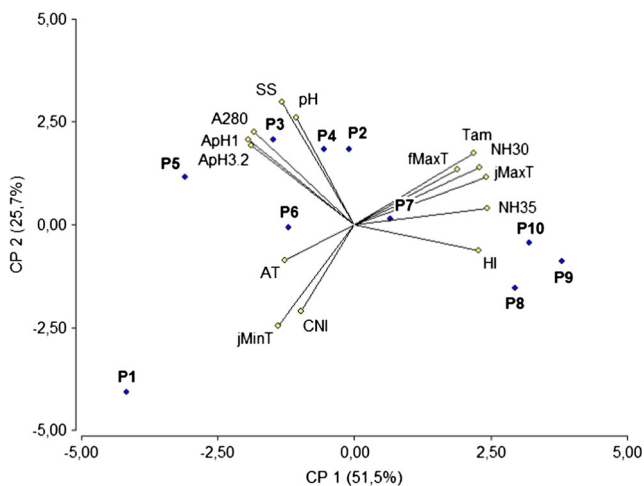
Primary metabolites	Secondary metabolites											
	SC		pH		TA		ApH1		ApH3.2		A280	
	Corr	<i>P</i>	Corr	<i>P</i>	Corr	<i>P</i>	Corr	<i>P</i>	Corr	<i>P</i>	Corr	<i>P</i>
Climate												
variables												
jMaxT	-0.24	0.51	-0.12	0.74	-0.47	0.17	-0.50	0.14	-0.43	0.21	-0.42	0.22
jMinT	-0.25	0.48	-0.16	0.65	0.45	0.19	0.15	0.69	-0.20	0.58	0.01	0.97
fMaxT	-0.14	0.69	0.04	0.91	-0.25	0.48	-0.24	0.51	-0.17	0.65	-0.20	0.58
HI	<i>-0.62</i>	0.05	<i>-0.45</i>	0.19	<i>-0.19</i>	0.60	<i>-0.69</i>	0.03	<i>-0.54</i>	0.11	<i>-0.60</i>	0.07
TAm	-0.10	0.79	-0.05	0.89	-0.38	0.28	-0.40	0.25	-0.36	0.31	-0.27	0.46
NH30	-0.13	0.72	-0.08	0.83	-0.49	0.15	-0.40	0.25	-0.36	0.31	-0.36	0.30
NH35	-0.39	0.27	-0.27	0.45	-0.41	0.24	<i>-0.58</i>	0.08	-0.51	0.13	<i>-0.56</i>	0.09
CNI	-0.30	0.40	0.01	0.98	0.31	0.38	-0.04	0.91	0.17	0.63	-0.04	0.91

Significant correlations are represented in italics

SC sugar content, TA total acidity, ApH1 total potential in anthocyanins, ApH3.2 potential in extractable anthocyanins, A280 phenolic richness, jMaxT January mean maximum temperature, fMaxT February mean maximum temperature, jMinT January mean minimum temperature, TAm thermal amplitude during the ripening period, HI Huglin index, CNI cool night index, NH30 number of hours with a temperature over 30 °C during the ripening period, NH35 number of hours with a temperature over 35 °C during the ripening period

### Tannat composition at harvest

Spatial variability of Tannat composition (between plots) was greater than temporal variability (between growing seasons). Berries from the plot near the river (plot 1) and from plots 23 km away from the river (plots 8, 9, and 10) proved to have the most unbalanced composition in all the vintages and in average, specifically in primary metabolites. Total acidity is a



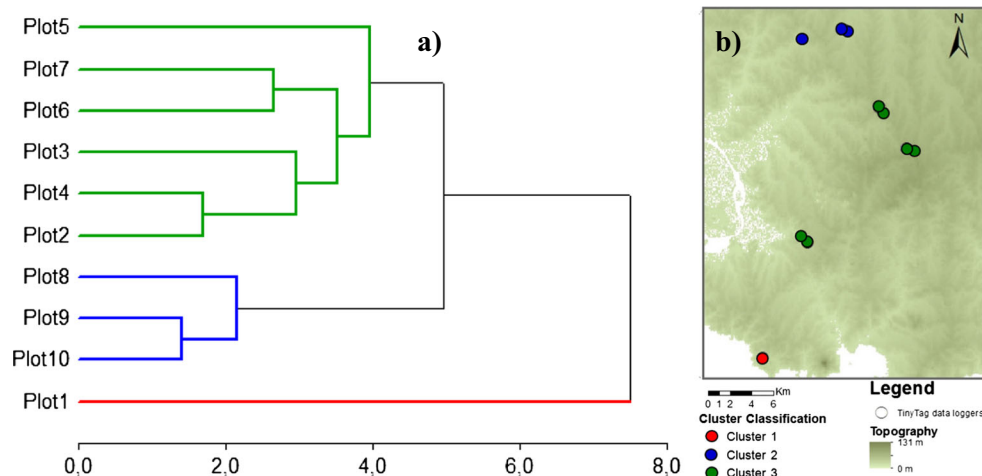
**Fig. 5** Principal component analysis for the three studied vintages. Eigen vectors of temperature and grape berry composition (yellow) and medium scores for each plot (blue). (SC sugar content, TA total acidity, ApH1 total potential in anthocyanins, ApH3.2 potential in extractable anthocyanins, A280 phenolic richness, jMaxT January mean maximum temperature, fMaxT February mean maximum temperature, jMinT January mean minimum temperature, TAm thermal amplitude during the ripening period, HI Huglin index, CNI cool night index, NH30 number of hours with a temperature over 30 °C during the ripening period, NH35 number of hours with a temperature over 35 °C during the ripening period)

component that is partially degraded (acid malic) and consumed during the ripening period (Kliewer 1973; Sweetman et al. 2014). Acidity is lessened under extreme hot summer conditions. Jackson and Lombard (1993) reported that cool nights associated with warm day temperatures, i.e., great daily thermal amplitude, were able to decrease acid levels in grapes compared to cooler daytime and warmer nighttime conditions. That could be the case of plots 8 to 10. Those plots, far away from the river, with more heat accumulation, have had the least acid berries at harvest, showing a possible effect on malic acid degradation by high temperatures (Sweetman et al. 2014).

In the same way, it is known that temperatures (particularly high thermal conditions during ripening) seem to be the most limiting climatic factor for the biosynthesis of anthocyanins, causing inhibition of this process (Mori et al. 2007; Goto-Yamamoto et al. 2009; Barnuud et al. 2014) and a decrease of this compound by degradation (Mori et al. 2007; González-Néves et al. 2010). Barnuud et al. (2014) reported that berry anthocyanin concentrations were significantly and inversely related to temperature experienced between véraison and maturity over a 700-km sampling transect in Western Australia wine region. At a finer scale, a similar temperature gradient over a shorter distance is likely to differentiate plots situated away from the river with high summer temperatures affecting final polyphenolic composition in the grapes and shaping low-er content in anthocyanins compared to plots near the river.

For the studied period, berries harvested at plots situated between 11 and 22 km from La Plata River (plot 5 and in other order plots 2, 3, and 4) showed less variability in SC, ApH1, and A280 over the three vintages. This characteristic of stability is essential to wine production and potential quality in wines. Under the Uruguayan conditions for Tannat

**Fig. 6** Cluster classification (Ward method) of the plots (a) and corresponding location in the region (b)



winemaking, González-Néves et al. (2010) studied optimum levels of polyphenol index related to quality. They showed the importance of those indices for the oenological assessment of the grapes and for the winemaking conditions. The extractability of anthocyanins was greater in berries harvested at plot 1 in all the studied vintages. Despite the fact that it was the poorest plot in anthocyanin potential, their extractability was as easy as for the berries from other plots, even when extraction of anthocyanins is difficult in this variety.

Berries from adjacent plots (i.e., plots 2 and 3 or plots 4 and 5) showed more significant variability in SC and TA than in potential in extractable anthocyanins and phenolic richness.

### Tannat response to temperature

Multivariate analyses of berry composition and temperature variables have discerned at least three features: (1) Tannat sensitivity to spatial variability of temperature varied over the vintages, (2) correlations between berry composition and temperature variables increased (in value and number) under dry ripening conditions, and (3) correlations between secondary metabolites and spatial variability of temperature were greater than those between primary metabolites of Tannat and spatial variability of temperature.

This is likely because complex vintages, e.g., rainy summers, could promote major winegrower interventions (soil practices, canopy management, and intensive phytosanitary use) to obtain quality grapes. Consequently, final composition of grapes is a complex response of several factors, in addition to temperature. Clingeffer (2010) reported that vineyard practices could minimize the impact of variability in climatic conditions from season to season. Canopy management for an optimum plant balance (source/sink ratio) and success in phytosanitary treatments for good fruit quality could be determinant to final composition for Uruguay conditions.

Across these three vintages, the correlations between temperature and primary metabolites of grapes were lower than

those between the secondary metabolites. Tannat secondary metabolites were more correlated to the climate variables as HI ( $r > -0.6$ ) and NH35 ( $r > -0.56$ ) demonstrating more sensitiveness. Analyzing correlations by vintage, similar results were found with stronger relationship between temperatures and secondary metabolites, as in the PCA of 2013. For that year, daily thermal amplitude was the component more correlated to berry composition in those vineyards: with SC ( $r = -0.76$ ), ApH1 ( $r = -0.9$ ), ApH3.2 ( $r = -0.94$ ), and A280 ( $r = -0.92$ ). These results are in agreement with the discussion above, regarding secondary metabolites being likely more affected by mesoscale temperatures in the studied region. Tannat anthocyanins were higher in berries from cooler plots at night (as far as 18.3 km for La Plata River) than those from the warmer plots at night. This corroborates results of Mori et al. (2007) and Barnuud et al. (2014). Indeed, the higher levels in phenol richness were found in the berries harvested at plots situated as far as 18.3 km from the river.

Even if vintage quality was not our focus, quality varied from 1 year to another. The highest levels in SC and ApH1 in berries of Tannat over the region were reached in 2012, the coolest vintage of the study in terms of heat accumulation (GDD). That contrasts with the results found by Baciocco et al. (2014) in Bordeaux (France). This work looked for the climatic factors that are critical to differentiating overall vintage quality. In this region, the best red wine vintages are associated with higher temperatures, large heat accumulations (HI and GDD), and low precipitation (especially during ripening), due to the balance between sugar accumulation and acid loss. Contrasting results could be explained possibly because the climate of Bordeaux does not belong to the same Köppen-Geiger class (Kottek et al. 2007) that in Uruguay (temperate summer in Bordeaux vs. hot summer in Uruguay; *Cfb* and *Cfa*, respectively), and in this class, heat accumulation is critical for wine quality.

Using cluster analysis, plots were divided into three groups that revealed the temperature gradient over the region. The

same grouping was observable in the PCA analysis (Fig. 5). The first group, shaped by plot 1, was associated with high minimum temperatures, while the second group (plots 8 to 10) was related to high maximum temperatures and large daily thermal amplitude, demonstrating the decreasing influence of the river inland. The third group (plots 2 to 7) was the most related to berry composition, confirming that they are the most balanced vineyards for wine production.

### Limits of the study

The use of thermal sensors installed in the canopy helped to study the grapevine response to temperature at fine scale. It is relevant as Matese et al. (2014) discussed in their work, because they express the real thermal conditions experienced in the vineyards. However, there is an indirect method to investigate temperature effects on viticulture as defined by Bonada and Sadras (2015). For the authors, the indirect methods rely on natural gradients from variations in space or time, and results are inferred from comparisons between thermally contrasting regions or vintages. In consequence, the results could be misinterpreted and may overlook secondary effects. In the case of our study, different cultural practices were performed over the region. The selection of contiguous plots was used to minimize the vinegrower management effect, as well as the different soil types (similar over the region and different on contiguous plots). Nevertheless, Tannat composition at harvest was assessed during the ripening which is the period with more grapevine sensitivity to temperature.

### Conclusions

The temperature loggers installed in the vineyards of Canelones and Montevideo departments contributed to increase the knowledge on climate in the coastal wine-producing region of Uruguay in terms of spatial variability of temperature at fine scale. It is an interesting approach to understanding how real temperatures in vineyards impact grapevine functioning at that scale.

Results showed significant spatial variability in temperature, greater than temporal variability in southern Uruguay. Temperature differences were identified in daily thermal amplitude and maximum temperature during the growing season and ripening period of grapes due to proximity of the sea and topography. Analysis of extreme maximum temperatures helped in identifying how high temperatures could affect grapevine physiological functioning and hence final grape composition.

Even if berry composition at harvest is the result of several factors that have an effect on vinegrape physiology and development, our study has allowed the development of knowledge on the relationships between Tannat berry compounds and temperature over the region. It appeared that berry composition

responded to temperature and its relation is year dependent and stronger in secondary metabolites. For Uruguay with significant seasonal climate variability, it is important to determine when grapevine behavior is strongly influenced by climate and how winegrowers, through their cultural practices, would have the possibility to intervene in order to improve fruit quality.

The increasing knowledge of spatial temperature variability and its relationships with grape berry composition contributes to improving vineyard management during the ripening period. These results lead to further investigation on adaptability of vineyards of southern Uruguay to climate variability in the changing climate context.

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**Compliance with ethical standards** We declare that the experiment complies with the current laws of Uruguay. This article does not contain any studies with human participants or animals performed by any of the authors.

**Conflict of interest** The authors declare that they have no conflict of interest.

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