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Bioclimatic zoning of Argentinian Malbec grape productivity regions by means of a unique combined index

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ABSTRACT: Climate conditions are the main factor controlling winegrape production worldwide. Establishing the impact of climatic conditions on grape production allows for evaluation of the suitability of a given region for winemaking. Given the relevance of Malbec wine production in Argentina, this study was devoted to deriving a unique combined index (UCI) for assessing the suitability of Malbec grape production (MGP) in the country. The index is a zoning tool that also quantifies the degree of suitability both in terms of temporal and spatial behavior. We used monthly mean temperature and precipitation data from a set of stations over the main wine-making regions of Argentina together with MGP data from Mendoza for the period 1979–2014. First, the co-variability between a set of bioclimatic indices and MGP was explored in order to identify the climatic variables that most strongly impact year-to-year variability of MGP. Growing season temperature, cool night index, growing season thermal amplitude and growing season precipitation were found to be the bioclimatic indices significantly correlated with MGP. This analysis also identified the ranges of each climatic variable corresponding to upper, normal and lower than normal MGP, allowing the definition of categories for each individual climatic variable. The individual categorized indices were then combined into the UCI, which quantifies MGP suitability. Finally, the UCI index was evaluated in terms of both its spatial and temporal behavior, and its utility as a tool for characterizing the suitability for MGP was demonstrated.

KEY WORDS: Bioclimatic zoning · Suitability · Malbec · Climatic factors · Argentina

1. INTRODUCTION

Wine production from *Vitis vinifera* L. is largely controlled by climate conditions during the growing season (Jones & Davis 2000, Fraga et al. 2016). Climate conditions have a great influence on the vine–fruit–wine continuum, affecting (1) vine growth and development by affecting photosynthetic rate, (2) grape composition and (3) wine sensorial characteristics. In particular, temperature and precipitation play an important role through the 3 main phenological stages of the growing season: (1) bud-break, initiated during spring; (2) bloom, initiated in late spring and early summer; and (3) veraison, which is the onset of ripening to harvest, initiated during summer (Ramos & Martínez-Casasnovas 2010). Temperature is the climatic factor that has the most influence on phenology and productivity of vines as well as on the composition and quality of grapes, and consequently, the quality and style of wines (Soar et al. 2008). For instance, grapevines start their annual growth cycle in the spring, with bud break initiated at a 10°C base temperature (Winkler et al. 1974), and reach their optimal photosynthetic response within the range

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20–35°C, depending on a combination of other factors such as water availability (Carbonneau et al. 1992). Moreover, to ensure optimal quality and well-balanced wines, warm daytime temperatures and cool nighttime temperatures are required during the period from ripening to harvest (Jones et al. 2005). The amount and seasonal distribution of precipitation also plays a key role, as it widely governs soil moisture and grapevine water potential during the growing season. In this sense, high water availability conditions are of utmost relevance for the vines at the beginning of the growing season, while low water availability conditions are needed at the end of the growing season from flowering to ripening (Jones & Davis 2000). Moreover, water supply to the grapevines during the ripening process plays a key role in the composition, yield and quality of the grapes and wine (Myburgh 2003). In summary, climate conditions encompassing a range of temperatures and precipitation may have a different impact on grape production, depending on the stage of plant development.

Owing to the direct influence of environmental conditions on vine phenology and grape composition, climatic conditions play a key role in assessing the suitability of a given region for winegrape zoning, and ultimately, winegrape production (Vaudour & Shaw 2005). Accordingly, the influence of climatic conditions on the suitability of winegrowing areas may be assessed through the viticultural zoning technique. This technique is based on bioclimatic indices that quantify the influence of climate on the development of the vine and the ripening of grapes, and helps in the selection of the proper variety for each zone. In this context, well-known bioclimatic indices have been used to conduct zoning studies to assess the climatic suitability of winegrape regions in different areas of the world, and to examine the potential impact of climate change on wine production. Examples of bioclimatic indices are the Winkler index (WI; Winkler et al. 1974), growing season mean temperature (GST; Hall & Jones 2009), Huglin heliothermal index (HI; Huglin 1983), cool night index (CN; Tonietto & Carbonneau 2004) and the dryness index (DI; Riou et al.1994), among others. A large number of viticultural zoning studies based on different bioclimatic indices and/or a combination of a set of indices are available for Europe (Malheiro et al. 2010, Moriondo et al. 2013, Fraga et al. 2014a, Irimia et al. 2014), the United States (Jones et al. 2010, Diffenbaugh & Scherer 2013), Australia (Hall & Jones 2009) and New Zealand (Anderson et al. 2012). For South America, only Cabré et al. (2016) and Montes et al. (2012) have analyzed the climatic potential for viticulture over central-western Argentina and central Chile, respectively, which are the main wine producing regions in South America (OIV 2015). These studies performed a climatic classification of the main grape growing regions based on several bioclimatic indices, including WI, GST, HI, CN and DI.

Although most of the indices used in the aforementioned studies are related to the vegetative cycle of the variety or potential grape quality for wine production, some of them have also been used to assess grape and/or wine production. Lorenzo et al. (2013) used WI and HI to assess the relationship between climate, grape production and wine quality in Spain. Ramos et al. (2008) used WI and GST, among others, to evaluate the climatic impact on grape production in northeast Spain. Santos et al. (2011) developed a statistical grapevine yield model for Portugal based on a set of climate parameters as predictors, including GST and precipitation. Later, Santos et al. (2013) used a time series of wine production in Portugal and monthly temperature and precipitation data to develop a statistical tool for wine production, by means of statistical modeling using both linear regression and logistic approaches. Fraga et al. (2014b) used the dryness and hydrothermal indices, monthly mean temperature and precipitation for selected months to assess the extent to which climate variability affected wine production in Portugal. Irimia et al. (2014) evaluated the suitability of climate, relief and soil for different wine types and qualities in Romania.

Argentina is the leading wine producer in South America in terms of volume and cultivated area, and is the 5th largest producer in the world (OIV 2015). The central-western region of Argentina is the traditional wine growing area, extending to the eastern slope of the Andes from 22° to 43° S (Fig. 1). It is divided into 3 main regions: (1) the Northwest Region, between 22° and 29° S; (2) the Cuyo Region, between 30° and 36° S (this area comprises the provinces of Mendoza and San Juan); and (3) the Northern Patagonia Region, between 36° and 43° S. Vineyards in the Northwest Region are located over an area ranging from 1500–3000 m a.s.l. elevation, being the highest vineyards worldwide (Fig. 1). In the Northern Patagonia Region, vineyards are typically at altitudes around 300 m. The Cuyo Region is the main wine producing area, and Mendoza is the province with the largest amount of wine production. This region is characterized by arid to semi-arid conditions, with total annual precipitation around 250 mm (concentrated during the growing season), with maxima of around 50 mm during March, and maximum temper-

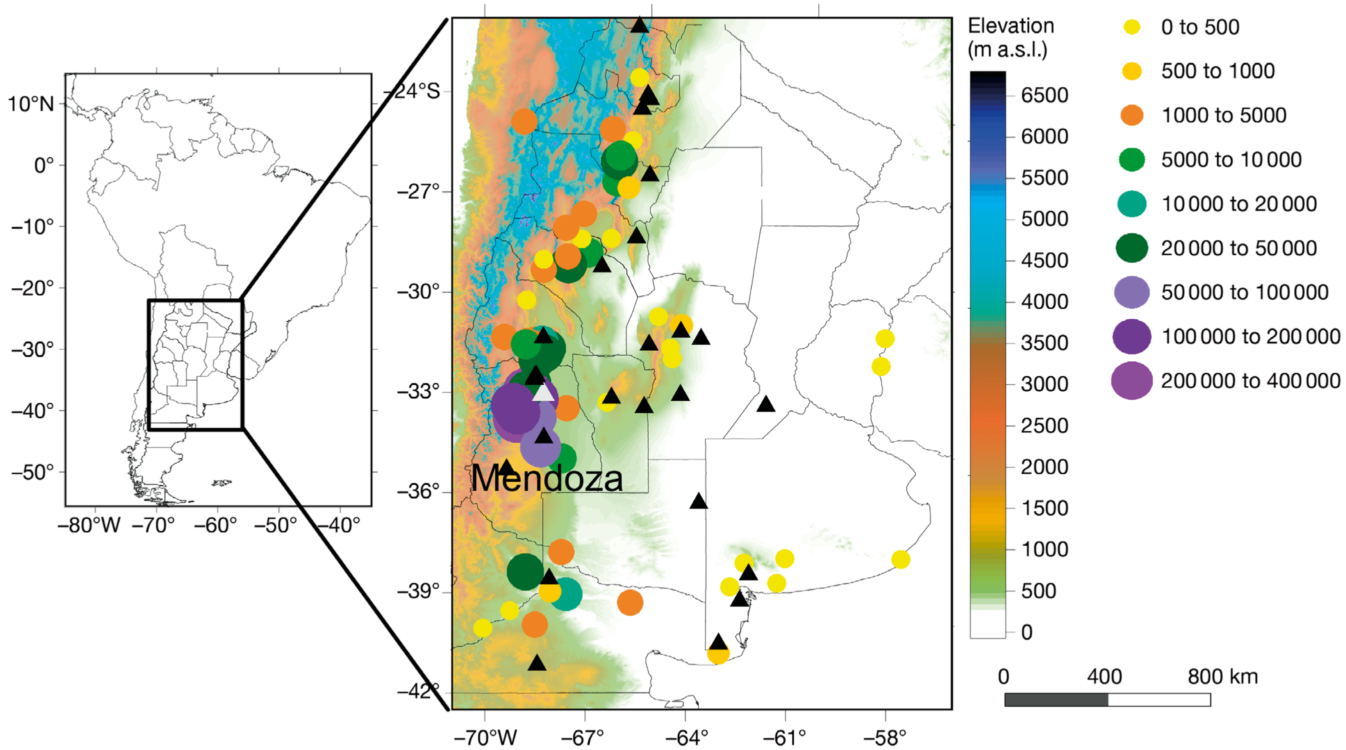

Fig. 1. Study region and spatial distribution of annual mean Malbec grape production (MGP; in quintals; 1 quintal = 100 kg) for the period 2001–2014. Colored dots: production location and amount according to the scale displayed; black triangles: meteorological stations listed in Table 1; grey triangle: San Martin station. Color shading: topography. Mendoza Province is also indicated

atures in the 27–30°C range during the growing season. With such a climate, vineyards are typically grown under irrigated conditions. Within this region, vineyards are located at a wide range of altitudes, from 450–1500 m. The main cultivars grown of high enological quality — Malbec, Bonarda, Syrah and Cabernet Sauvignon — stand out among the red grapes, and Pedro Gimenez, Torrontés Riojano and Chardonnay among the white grapes. In addition, *Vitis vinifera* L. cv Malbec, native to southwestern France, is a middle-maturing red grape variety considered as the emblematic cultivar for wine production in Argentina, and is the most widely planted grape variety in the country (Fanzone et al. 2010). MGP is important for the regional economy as well as national and international markets. Regarding regional and national economies, Mendoza accounts for 84% of the Malbec grape production (MGP) cultivated over 34 000 ha (INV 2016), and 52% of the total grape production. Concerning external markets, Argentinian wineries have achieved significant growth, and attained a strong global position (no. 1 exporter worldwide) with regards to the Malbec grapevine, which is recognized as one of the best quality cultivars in the world.

Despite the economic importance of the wine industry in Argentina, few studies have focused on the potential impact of climate conditions on the vine's yield in the region (Agosta et al. 2012, Quenol et al. 2015, Cabré et al. 2016), and there is a lack of studies focusing specifically on assessing climatic suitability for MGP in Argentina. In order to assess climatic suitability, it is necessary to first identify the key bioclimatic indices and their ranges for this specific region and this specific variety. Ranges derived from other regions of the world may not be suitable for every region or every variety (as highlighted in Montes et al. 2012). Additionally, there is a need to identify a multi-criteria climatic index to better represent the complex climatic suitability response of this specific variety in the studied region. It is worth mentioning that a combination of several bioclimatic indices allows a better description of the climatic structure and suitability of a given wine region for a specific variety, as shown by Tonietto & Carbonneau (2004) and Fraga et al. (2014a), among others. Therefore, this study aimed to derive a new index for bioclimatic zoning of MGP in Argentina based on the co-variability of a set of bioclimatic indices and actual Malbec grape productivity, taking into account that interannual climate variability affects interannual grape production, thus affecting the yield (Fraga et al. 2014b) and quality of grapes and typicity of wines (van Leeuwen & Darriet 2016).

The importance of building this index is 3-fold: (1) it enables the definition of a proper zoning index for Malbec production in Argentina, (2) it allows measurement of the diverse degree of suitability or non-suitability of Argentinean MGP areas and (3) it can be used to assess the potential impact of climate change on Malbec production in the country.

2. DATA AND METHODS

2.1. Grape production data

Grape production data was provided by the 'Instituto Nacional de Vitivinicultura' of Argentina (INV). The data consists of Mendoza's total annual amount of MGP in quintals (100 kg) for the period 1993–2014. Mendoza province is where the majority of grapes are produced, accounting for 84 % of the Argentinian MGP, around 1.5 million quintals yr^{-1}. In this study, only the Malbec variety was considered, as it is one of the principal varieties in the country, accounting for 52 % of total grape production in Mendoza. Additionally, annual MGP time series for a number of locations in Argentina available for the period 2001–2014 were also used. Fig. 1 displays the spatial distribution and amount of grape production for the Malbec variety averaged over the period from 2001–2014.

The time series of MGP in Mendoza exhibits a significant positive trend (increase of 9 % yr^{-1}), mainly associated with an increase in the planted area. Additionally, improvements in agricultural practices may also have had an impact on the MGP trend. Therefore, in order to avoid including non-climatic forcings on the behavior of the year-to-year variability in MGP, the linear trend was removed.

2.2. Climate data

Monthly mean, minimum and maximum temperatures and monthly accumulated rainfall data from 29 stations from the National Meteorological Service (SMN) of Argentina were used. Table 1 displays the list of stations, which are also indicated in Fig. 1.

Station data records for the period 1960–2014 were available. Their quality was carefully examined. All the selected series had $<20\%$ of monthly rainfall data missing, and no stations had records affected by changes in location or instrumentation. The meteorological data at Stn San Martin in Mendoza for the period 1993–2014 was used to identify consistent relationships between bioclimatic indices and MGP in Mendoza. This station was selected due to its location near the Mendoza department where the largest amount of Malbec grapes are produced, as displayed in Fig. 1. Data for the other stations for the period 2001–2014 were also used for evaluation.

Table 1. Meteorological stations used for computing the climatic indices

Station	Lat (°S)	Long (°W)	Province
La Quiaca Obs	22.06	65.36	Jujuy
Jujuy UN	24.10	65.11	Jujuy
Jujuy Aero	24.23	65.05	Jujuy
Salta Aero	24.51	65.29	Salta
Tucumán Aero	26.51	65.06	Tucumán
La Rioja Aero	29.23	66.49	La Rioja
Catamarca Aero	28.36	65.46	Catamarca
San Juan Aero	31.34	68.25	San Juan
Villa Dolores Aero	31.57	65.08	Córdoba
Córdoba Aero	31.19	64.13	Córdoba
Pilar Obs	31.40	63.53	Córdoba
San Martin	33.05	68.25	Mendoza
Mendoza Aero	32.50	68.47	Mendoza
Mendoza Obs.	32.53	68.51	Mendoza
San Luis Aero	33.16	66.21	San Luis
Villa Reynolds Aero	33.44	65.23	San Luis
Rio Cuarto Aero	33.07	64.14	Córdoba
Chacras de Coria	32.59	68.52	Mendoza
Venado Tuerto	33.40	61.58	Santa Fe
Malargue Aero	35.30	69.35	Mendoza
San Rafael Aero	34.35	68.24	Mendoza
Anguil INTA	36.30	63.59	La Pampa
Neuquén Aero	38.57	68.08	Neuquén
Bariloche Aero	41.09	71.10	Rio Negro
Hilario Ascasubi INTA	39.23	62.37	Buenos Aires
Bahía Blanca Aero	38.44	62.10	Buenos Aires
Maquinchao	41.15	68.44	Rio Negro
Viedma Aero	40.51	63.01	Buenos Aires
Esquel Aero	42.56	71.09	Chubut

2.3. Methodology

For San Martin station, 11 bioclimatic indices were computed; 9 accounting for thermal conditions based on either mean or extreme temperatures and 2 based on precipitation. The growing season for each year corresponds to the period from October of the year before harvest to April. The indices based on thermal conditions include the classical WI (Winkler et al. 1974), accounting for the degree-days above a given threshold (normally 10°C) during the growing season (this is also known as the growing-degree-day [GDD] index but with the Winkler scale); the GST, defined as the mean temperature during the growing season (Hall & Jones 2009); the monthly mean maximum (GSTx) and minimum temperatures (GSTn) during the growing season; the mean thermal amplitude during the growing season (GSTA); the CN (Tonietto & Carbonneau 2004), defined as the monthly mean minimum temperature during the month before harvest (March); the daily maximum temperature (dGSTx) and daily minimum temperature (dGSTn) recorded during the growing season; and the maximum thermal amplitude based on the absolute maximum and minimum temperatures (dGSTA).

To account for water availability, and due to the lack of reliable information on soil moisture in the region, monthly precipitation was used. Two indices based on precipitation were included: precipitation accumulated during the growing season (GSP), which was found to have a major impact on the grape yield in Mendoza (Agosta et al. 2012); and total annual accumulated precipitation (P).

A summary of how these bioclimatic indices were computed is given below:

$$\mathrm{WI} = \sum_{\mathrm{October}}^{\mathrm{April}} (\bar{T} - 10) \times d \tag{1}$$

$$\mathrm{GST} = \frac{1}{7} \sum_{\mathrm{October}}^{\mathrm{April}} \bar{T} \tag{2}$$

$$\mathrm{GST}x = \frac{1}{7} \sum_{\mathrm{October}}^{\mathrm{April}} \bar{T}x \; and \; \mathrm{GST}n = \frac{1}{7} \sum_{\mathrm{October}}^{\mathrm{April}} \bar{T}n \tag{3}$$

$$\mathrm{GSTA} = \frac{1}{7} \sum_{\mathrm{October}}^{\mathrm{April}} (\bar{T}x - \bar{T}n) \tag{4}$$

$$\mathrm{CN} = \bar{T}n(March) \tag{5}$$

$$\begin{gathered} \mathrm{dGST}x = \mathrm{MAX}_{\mathrm{1Oct}}^{\mathrm{30Apr}}(Tx) \\ \text{and } \mathrm{dGST}n = MIN_{\mathrm{1Oct}}^{\mathrm{30Apr}}(Tn) \end{gathered} \tag{6}$$

$$\mathrm{dGSTA} = \mathrm{dGST}x - \mathrm{dGST}n \tag{7}$$

$$\mathrm{GSP} = \sum_{\mathrm{October}}^{\mathrm{April}} \bar{P} \tag{8}$$

$$P = \sum_{\mathrm{May}}^{\mathrm{April}} \bar{P} \tag{9}$$

where $\bar{T}$, $\bar{T}x$ and $\bar{T}n$ are the monthly mean, monthly maximum and monthly minimum temperatures, respectively, P is annual precipitation and $\bar{P}$ is the monthly accumulated precipitation. T, Tx and Tn are the daily temperature, daily minimum and daily maximum temperatures, respectively; d is the number of days in each month. Note that the WI index was computed using monthly mean temperatures and hence it may misrepresent the accumulated heat (Gu 2016).

It is worth noting that the mean annual cycle of precipitation at the San Martin station is characterized by minimum rainfall during the winter months (<5 mm mo^{-1} during June and July) and an increase in rainfall from August reaching a maximum of 50 mm mo^{-1} during March. Hence, the growing season is when most of the rainfall occurs (80% of the annual rainfall). Besides the bioclimatic indices described, and in accordance with previous studies (Santos et al. 2011, Fraga et al. 2014b), monthly mean temperature and precipitation for individual months were considered as potential bioclimatic indices for production zoning.

Some of the indices evaluated in this study have already been used in other studies together with previously defined classes accounting for grape suitability, ripening potential and wine quality (Fraga et al. 2014b and references therein). However, it is apparent that the range of values for each index is highly dependent on the particular viticultural region. Moreover, the classes in which each of the indices are classified is also sensitive to the particular grape variety. Therefore, the classes for each of the bioclimatic indices will be identified as part of the process of deriving the regional index for Malbec in Mendoza.

The procedure to identify the bioclimatic indices that are more strongly related to grape production is based on inspection of interannual variability of both climatic variables and MGP. The analysis was performed based on data from the San Martin station and MGP for the whole Mendoza province. As mentioned above, the time series of MGP were detrended in order to avoid including changes in planting areas and/or changes in technological practices. Inspection of the time series of the bioclimatic indices at San Martin station revealed that the indices based on mean, maximum and minimum temperatures exhibit a significant trend, therefore the linear trend was also removed. All detrended variables analyzed in this study were found to be quasi-normally distributed.

Results from the time series analysis were then used to select the bioclimatic indices that emerged as significantly correlated with the MGP time series. In this way, bioclimatic zoning is based on the sensitivity of the actual grape production to climate conditions in agreement with Tonietto & Carbonneau (2004), who recognized that the viticultural climate is established based on climatic and viticultural information. Though most of the zoning exercises are based on bioclimatic indices associated with wine quality, several authors have also complemented the information from bioclimatic indices with either production data or information on the extension of wine regions (e.g. Hall & Jones 2009, Jones et al. 2010, Anderson et al. 2012, Fraga et al. 2016).

The 33rd and 66th percentiles of the MGP time series from all production locations were computed, and the ranges of bioclimatic indices for MGP above the 66th percentile, within the 66th to 33rd percentiles, and below the 33rd percentile were used to define individual indices for each of the bioclimatic variables, indicating ranges for optimum, adequate and limiting conditions for grape growth. Finally, the categories of the selected bioclimatic indices were integrated to build a unique combined index (UCI), and its spatial and temporal behavior were compared with the spatial and temporal behavior of the actual MGP.

Table 2. Correlation coefficients between individual bioclimatic indices at the San Martin station and Malbec grape production (MGP) for Mendoza computed for the period 1993–2014. Significance is indicated in **bold** (at the 5% level) and *italics* (at the 10% level), respectively. (−1) and (0) indicate that the monthly mean values of either temperature (T) or precipitation (P) correspond to the year before harvest and the year of harvest, respectively. WI: Winkler index; GST: growing season mean temperature; GSTx: monthly mean maximum temperature during the growing season; GSTn: monthly mean minimum temperature during the growing season; GSTA: mean thermal amplitude during the growing season; CN: cool night index; dGSTx: daily maximum temperature; dGSTn: daily minimum temperature; dGSTA: absolute temperature amplitude; GSP: growing season precipitation accumulation

Index	Correlation	Index	Correlation	Index	Correlation
WI	**0.4**	T_{May} (−1)	0.27	P_{May} (−1)	−0.26
GST	**0.42**	T_{Jun} (−1)	*0.38*	P_{Jun} (−1)	**−0.45**
GSTx	*0.39*	T_{Jul} (−1)	−0.06	P_{Jul} (−1)	**−0.62**
GSTn	−0.09	T_{Aug} (−1)	0.09	P_{Aug} (−1)	−0.2
GSTA	**0.53**	T_{Sep} (−1)	0.05	P_{Sep} (−1)	−0.05
CN	*−0.35*	T_{Oct} (−1)	0.07	P_{Oct} (−1)	−0.29
dGSTx	0.19	T_{Nov} (−1)	**0.4**	P_{Nov} (−1)	−0.2
dGSTn	0.15	T_{Dec} (−1)	**0.61**	P_{Dec} (−1)	−0.26
dGSTA	0.02	T_{Jan} (0)	0.17	P_{Jan} (0)	−0.17
GSP	**−0.42**	T_{Feb} (0)	−0.11	P_{Feb} (0)	0.1
P	−0.29	T_{Mar} (0)	0.01	P_{Mar} (0)	−0.24
		T_{Apr} (0)	0.21	P_{Apr} (0)	**−0.54**

3. RESULTS

3.1. Interannual variability of MGP and bioclimatic indices

Inspection of the co-variability between the MGP and bioclimatic indices allowed us to identify the key bioclimatic indices that impact the MGP. The correlation coefficients between each of the indices computed for the San Martin station and MGP for Mendoza are displayed in Table 2.

WI, GST, GSTx, GSTA, CN and GSP arose as the bioclimatic indices significantly correlated with MGP at Mendoza (at the 5% level, except CN and GSTx, for which the correlation coefficients were significant at the 10% level). Among the thermal indices, WI, GST, GSTx and GSTA were found to be positively correlated with MGP while CN yielded a negative correlation. These results suggest that warmer (colder) than normal thermal conditions during the growing season and colder (warmer) than normal minimum temperatures during the month before harvest are more (less) favorable for MGP in Mendoza. Moreover, temperature during December arose as the thermal index with the highest correlation, suggesting that the largest impact of thermal conditions on grape productivity occurs during the bloom period.

The positive effect of temperature, measured by the positive correlation with GST, GSTA, GSTx, and November and December temperatures may be associated with high levels of photosynthetic activity that induce complete maturation, as discussed by Moriondo et al. (2015). Jones & Davis (2000) also found that warm conditions during floraison and veraison and dry conditions during maturation were beneficial for the composition and quality of grapes. Likewise, several studies have also reported low temperatures and high precipitation at flowering as potential limiting factors on productivity in cooler climates (Vasconcelos et al. 2009 and references therein).

The CN index is one of the most important features for the synthesis of the compounds responsible for color and aroma in grapes (Kliewer & Torres 1972, Kliewer 1973). High daily temperature ranges with relatively cool nights during ripening tend to be beneficial for the production of high-quality wines, for example by synthesizing anthocyanins in grapes (Kliewer & Torres 1972). Though the CN index is more closely associated with quality of grapes, this variable has also been found to be strongly associated with production in other vineyards of the world (Fraga et al. 2014b).

It is important to note that some of the individual bioclimatic indices are not independent among each other (i.e. are highly correlated). This is the case for WI, GSTx, T_{Nov} (−1) and T_{Dec} (−1) (see Table 2 caption for detail), which are all strongly correlated with GST and GSTA (data not shown). Thus, in order to select independent indices, only GST, GSTA and CN were chosen.

Among the bioclimatic indices accounting for water availability, it was found that GSP, largely due to April precipitation, yielded a significant negative correlation with MGP. This result agrees with Agosta et al. (2012), who showed that growing season precipitation over central-western Argentina was negatively correlated with the yield in Mendoza, reinforcing the impact of precipitation on both grape production and yield even when vineyards are grown under irrigated conditions. Jones & Davis (2000) also reported that high precipitation during bloom may have a detrimental impact on yield, due to the effect of a lower fruit set and inflorescence differentiation. Moreover, rainfall during veraison may aggravate moisture-related problems and increase the need for cluster and/or berry selection during harvest. Moriondo et al. (2011) also suggested that the negative effect of rainfall in the months prior to harvest is possibly related to the dilution of berries during the ripening phase and the onset of fungal diseases triggered by high humidity.

Significant negative correlations were also found for monthly precipitation during the winter months (June and July). This would probably affect soil moisture conditions during the end of winter and the beginning of spring. However, vineyards in the target region are mostly irrigated, so the direct impact of anomalous precipitation along the phenological cycle is difficult to quantify. Consequently, GSP was selected because it quantifies the bulk impact of rainfall throughout the whole growing season.

Based on the results discussed above, a combined index (CI) was defined as the average of the normalized anomalies of the 4 bioclimatic indices selected:

$$\mathrm{CI}(k) = [\mathrm{GST}'(k) + \mathrm{GSTA}'(k) - \mathrm{CN}'(k) - \mathrm{GSP}'(k)] / 4 \qquad (10)$$

where k indicates individual years; $k = 1, N$ with N being the total number of years of the time series; (') indicates normalized anomalies computed as anomalies with respect to the climatological mean divided by the climatological standard deviation of the time series. The climatological standard deviation for the MGP time series is around 250 000 quintals.

Fig. 2 displays the time series of the normalized anomalies of MGP together with the CI. Recall that the mean MGP for Mendoza is around 1.5 million quintals yr^{-1} and the standard deviation of MGP is around 250 000 quintals. It is therefore interesting to note that the year-to-year variability of MGP is quite large, ranging from 40 % above to 33 % below the mean MGP. It is apparent from Fig. 2 that the year-to-year variability of the MGP is consistent with the year-to-year variability of the CI, suggesting that meteorological conditions have an impact on MGP. Moreover, the largest (smallest) anomalies of MGP usually occur simultaneously with the largest (smallest) anomalies of the CI, therefore, extreme climate conditions are highly relevant for extreme MGP amounts. The correlation coefficient between the 2 time series is 0.71 (significant at the 5 % level), indicating that 50 % of the variance of MGP is explained by the CI. Note that the correlation coefficients for individual bioclimatic indices displayed in Table 2 suggest that only a small percentage of the MGP variance can be explained by individual indices, but the CI yields a higher percentage of explained variance. Therefore, the CI allows for identification of the sensitivity of MGP to climatic conditions.

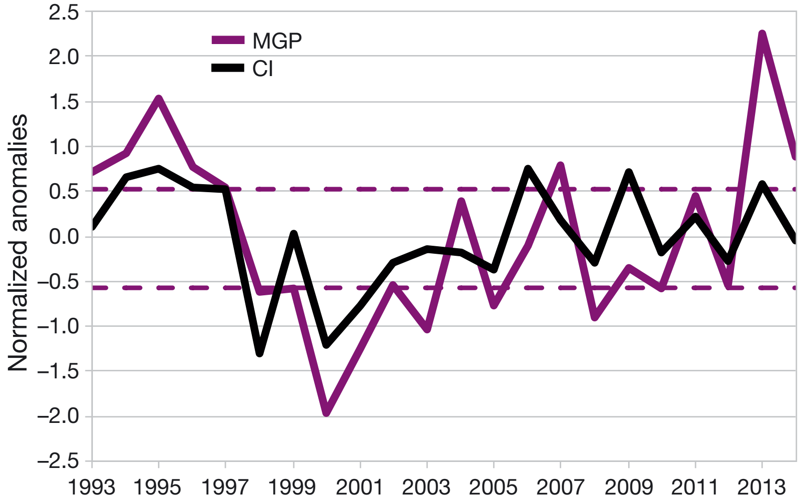

Fig. 2. Time series of normalized anomalies of annual Malbec grape production (MGP) in Mendoza (violet line) and combined index (CI; black line) computed at the San Martin station. Dashed lines denote the 33rd and 66th percentiles of MGP

In order to verify the contribution of the individual indices considered in the CI index, a stepwise multiple regression analysis was performed (data not shown). The analysis confirmed that the 4 individual indices were relevant, though the relative contributions of GST and CN were slightly larger compared with that of GSTA and GSP. Nevertheless, the modeled MGP time series using the results from the multiple regression analysis and using the CI index yielded very similar results (r = 0.79 and r = 0.71, respectively).

The analysis described above was the basis for defining individual indices based on each of the bioclimatic variables included in the definition of CI. First, the 33rd and 66th percentiles of the MGP time series were computed, taking into account MGP data from all production locations (displayed in Fig. 1). For each production location, the nearest meteorological station was selected to compute the bioclimatic indices. Then the ranges of the selected indices corresponding to MGP above the 66th percentile, between the 33rd and 66th percentile and below the 33rd percentile were identified to define the categories for each index: category 3 for values corresponding to MGP above the 66th percentile; category 2 for values within the 33rd to 66th percentile; category 1 for values corresponding to MGP below the 33rd percentile. Additionally, ranges for a non-suitability category (category 0) were also included, defined for values of the indices below the absolute minimum or above the absolute maximum, respectively. The scatter diagrams between MGP and each bioclimatic index computed for all production locations and the corresponding indices at the nearest station displayed in Fig. 3 summarize these results. Note that the scatter plots of each index against MGP have a rotated 'v' shape, revealing a range for the largest production and 2 ranges for medium, low and no production, respectively. The scatter plot for GSP is less consistent, mostly for ranges of low precipitation. This may be because irrigation is a common practice in the region, and

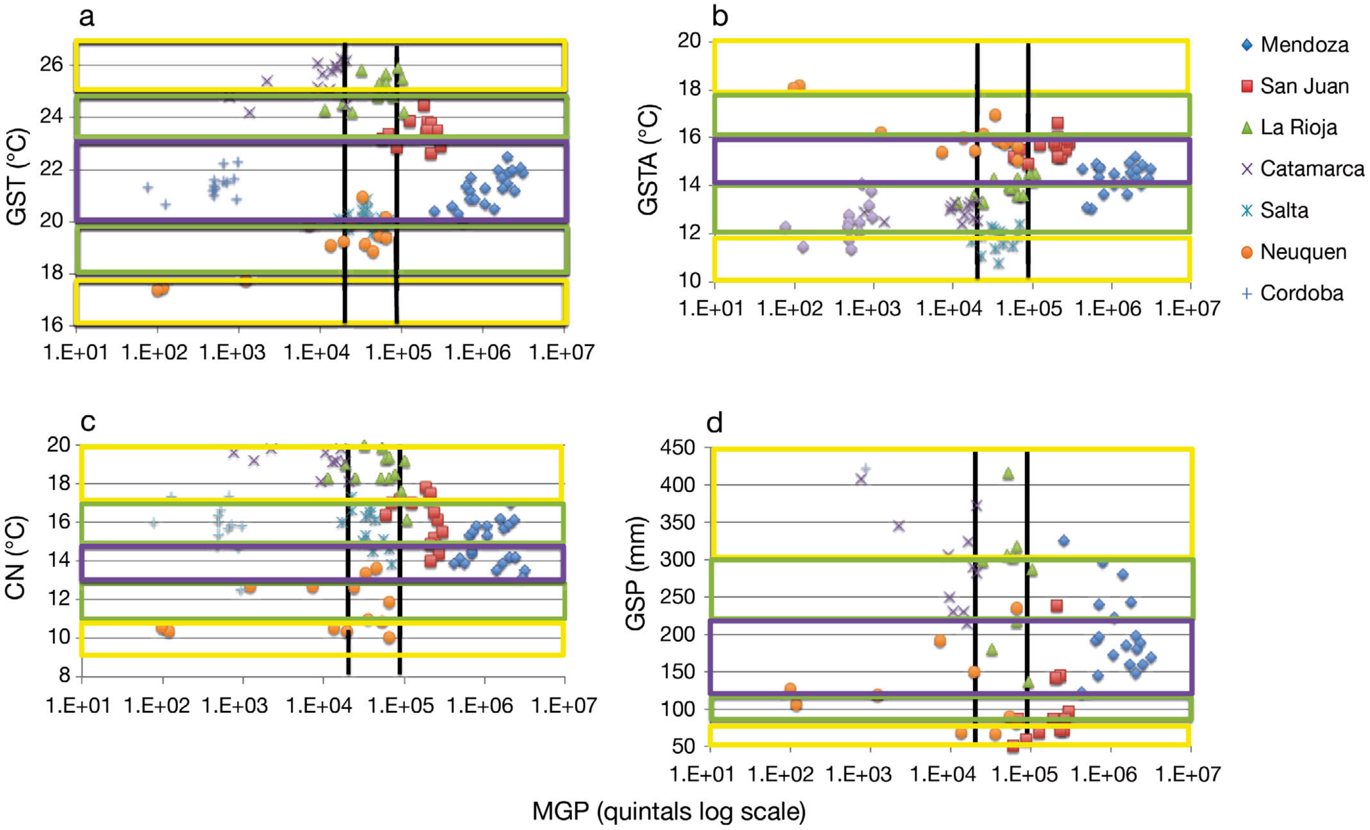

Fig. 3. Malbec grape production (MGP) (quintals in log scale) versus (a) growing season temperature (GST); (b) growing season mean thermal amplitude (GSTA); (c) cool night index (CN) and (d) growing season precipitation (GSP). Time series of MGP data from all locations displayed in Fig. 1 together with data from the nearest meteorological station for each location were used. Black threshold lines for categorization are indicated corresponding to the 33rd and 66th percentiles of MGP. Colored boxes highlight the ranges of the bioclimatic indices for category 1 (yellow boxes), category 2 (green boxes) and category 3 (violet boxes)

therefore the impact of precipitation deficits on MGP may be hidden.

Results from this analysis yielded the ranges for optimum, normal, low and non-suitability of MGP for each bioclimatic index. These categories allowed us to define individual indices for each bioclimatic variable, ranging from 0 to 3 as indicated in Table 3.

Following the literature (e.g. Tonietto & Carbonneau 2004), the CN index is usually categorized into 4 classes: very cool nights (CN ≤ 12°C); cool nights (12°C < CN ≤14°C); temperate nights (14°C < CN ≤18°C) and warm nights (CN > 18°C). Fraga et al. (2014a) considered only 2 categories for the CN: below or above 14°C; a CN index above the threshold being an indicator of better suitability for wine production in Portugal. The range of CN in this study is spread over a larger range and includes lower minimum temperature values compared to Fraga et al. (2014a) and Malheiro et al. (2010). The range corresponding to the largest MGP lies within the interval from 14 to 16°C, corresponding to the temperate nights class according to Tonietto & Carbonneau (2004). It is important to note that although the CN was selected among several bioclimatic indices due to its significant correlation with MGP, it is actually strongly associated with grape quality (Tonietto & Carbonneau 2004), and consequently, it also accounts for the quality dimension of the zoning technique.

The GST has also been included as an indicator of suitability in several studies around the world. Fraga et al. (2014a) used a range of suitability from 12–22°C. As shown in Table 3, the ranges identified here for the GST are warmer than the ranges identified in the literature, with the optimum range (from 20–23°C) falling within the hot classes identified in Fraga et al. (2014a). GSP was also used by Irimia et al. (2014), who identified a minimum of 250 mm for unirrigated vineyards.

It is important to take into account that here only one variety was evaluated, while most of the studies dealing with the categorization of bioclimatic indices for grape or wine production focus on several varieties, depending on the region (e.g. Fraga et al. 2014b for Portugal, Malheiro et al. 2010 and Moriondo et al. 2013 for Europe, Diffenbaugh & Scherer 2013 for North America). Jones (2006) indicated that the span of varietal ripening potential for Malbec grapes based on GST ranges from 16–19°C based on the main viticulture regions of the world. Note, again, that this range is well below the range identified for Mendoza, suggesting the need for local and regional studies to determine the climate suitability for any given variety in any given region.

Table 3. Bioclimatic indices, their ranges and categories for growing season temperature (GST), growing season thermal amplitude (GSTA), cool night index (CN) and growing season precipitation (GSP)

Range	Category	Range	Category
GST (°C)		**CN (°C)**	
≤16	$I_{\mathrm{GST}} = 0$	≤9	$I_{\mathrm{CN}} = 0$
(16–18]	$I_{\mathrm{GST}} = 1$	(9–11]	$I_{\mathrm{CN}} = 1$
(18–20]	$I_{\mathrm{GST}} = 2$	(11–13]	$I_{\mathrm{CN}} = 2$
(20–23]	$I_{\mathrm{GST}} = 3$	(13–15]	$I_{\mathrm{CN}} = 3$
(23–25]	$I_{\mathrm{GST}} = 2$	(15–17]	$I_{\mathrm{CN}} = 2$
(25–27]	$I_{\mathrm{GST}} = 1$	(17–20]	$I_{\mathrm{CN}} = 1$
>27	$I_{\mathrm{GST}} = 0$	>20	$I_{\mathrm{CN}} = 0$
GSTA (°C)		**GSP (mm)**	
≤10	$I_{\mathrm{GSTA}} = 0$	≤50	$I_{\mathrm{GSP}} = 0$
(10–12]	$I_{\mathrm{GSTA}} = 1$	(50–80]	$I_{GSP} = 1$
(12–14]	$I_{\mathrm{GSTA}} = 2$	(80–120]	$I_{GSP} = 2$
(14–16]	$I_{\mathrm{GSTA}} = 3$	(120–220]	$I_{GSP} = 3$
(16–18]	$I_{\mathrm{GSTA}} = 2$	(220–300]	$I_{GSP} = 2$
(18–20]	$I_{\mathrm{GSTA}} = 1$	(300–450]	$I_{GSP} = 1$
>20	$I_{\mathrm{GSTA}} = 0$	>450	$I_{GSP} = 0$

GSTA has not been commonly used as grape suitability indicator in the literature, and consequently, this variable has not previously been categorized into standard classes.

Finally, for each year, a combined index integrating the individual climatic indicators, referred to as the unique combined index (UCI), was defined in order to measure the suitability for Malbec variety grape production. The UCI is defined as follows:

$$\begin{cases} \mathrm{UCI}(k) = I_{\mathrm{GST}}(k) + I_{\mathrm{GSTA}}(k) + I_{\mathrm{CN}}(k) + I_{\mathrm{GSP}}(k) \\ \text{if every individual index} \neq 0 \\ \mathrm{UCI}(k) = 0 \text{ if any of the individual indices} = 0 \\ \text{where } k \text{ indicates year.} \end{cases} \tag{11}$$

The UCI index ranges from 4–12; UCI ≤ 3 indicates that at least one of the climatic conditions for MGP suitability are not fulfilled and UCI = 12 indicates the optimum climatic conditions for MGP. For each of the categories defined for the individual bioclimatic indices it is possible to describe the corresponding climate conditions as warm or cold and wet or dry; however, the UCI combines these categories and it may have the same value even with different climatic conditions. Nevertheless, the UCI should be interpreted in terms of its absolute value: the larger (smaller) the value of UCI the better (worse) the climatic conditions for MGP.

Other studies have defined combined indices based on different sets of bioclimatic characteristics (Malheiro et al. 2010 for Europe; Fraga et al. 2014a for Portugal; Tonietto & Carbonneau 2004 worldwide).

An advantage of the UCI defined here is its simplicity, but also the fact that the climatic variables included and their ranges are defined objectively in terms of their co-behavior with the MGP.

In order to evaluate the quality of the UCI index, the year-to-year variability of UCI computed with data from the San Martin station was compared with the year-to-year variability of MGP for Mendoza. Fig. 4 shows the 2 time series. It is apparent that the temporal evolution of UCI displays a strong correlation with the temporal evolution of the MGP amounts. The correlation coefficient is 0.62 (significant at the 5 % level), indicating that 38 % of the variance of Mendoza's MGP is explained by the combined climatic information described in the UCI. This supports the conclusion that the UCI represents an adequate tool for characterizing the suitability of MGP.

3.2. Bioclimatic zoning as represented by the UCI

Before evaluating the capability of UCI to reproduce the spatial distribution of MGP in Argentina, the spatial distribution of the climatological mean of the 4 bioclimatic characteristics included in its definition, together with the spatial distribution of the mean MGP amounts are displayed in Fig. 5. For GST, GSTA, CN and GSP, the areas where these indices reach values within the suitability range (see Table 3) spreads over regions where Malbec grapes are actually produced. As expected, over the northern Mendoza province where the MGP is the largest, all indices vary within the range of optimum suitability (indicated in the figure as the region bounded by violet lines). Moreover, the correspondence between better/worse climatic conditions with the larger/smaller amount of MGP is apparent.

Note that, as suggested in Fig. 1, the region where Malbec grapes are produced extends over a large region, encompassing very different climatic characteristics. Note also that for some of the bioclimatic variables the areas of suitability extend out of the main viticultural zone. This is apparent for GST, GSTA and CN. However, GSP is the variable that better delineates the region of grape suitability. It is worth noting that irrigation is a common practice in the region; however, it is not possible to include moisture amounts other than natural environmental conditions, and therefore the defined ranges do not take these practices into account.

Results of the spatial distribution of GST in this work are similar to those in Cabré et al. (2016); however, what is distinctive in this study is that the classes have not been taken from the literature but rather are associated with the actual amounts of grape production.

Finally, the spatial distribution of the UCI is displayed in Fig. 6. As for the MGP, the values of UCI have been considered in 3 categories: 3 < UCI ≤ 6; 6 < UCI ≤ 9 and above 9, indicating low, medium and high suitability, respectively. White areas indicate no suitability (UCI ≤ 3). Note that the extreme limits of each individual bioclimatic variable represent limiting factors for MGP. Overall, the spatial pattern of UCI is consistent with the actual distribution of the MGP. Stations with higher (lower) values of UCI are placed close to locations with higher (lower) MGP amounts. The UCI index defined here is consistent with the observed MGP, locating the area with best suitability over the northern part of the Mendoza province, where most Malbec grapes are produced. However, there are some areas where the UCI value is high, but grape production in that area is not. This index represents a basis for further studies focused on evaluating the impact of a changing climate on MGP in the region.

As mentioned previously, other studies from different viticultural regions of the world have also used indices for climatic zoning. Fraga et

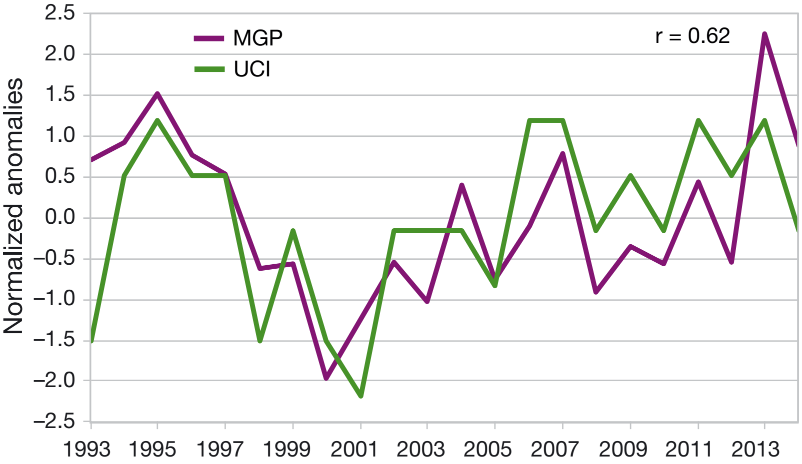

Fig. 4. Time series of normalized anomalies of the unique combined index (UCI) (green line) at the San Martin station together with normalized anomalies of mean Malbec grape production (MGP) for Mendoza (violet line). The correlation coefficient between time series is also indicated

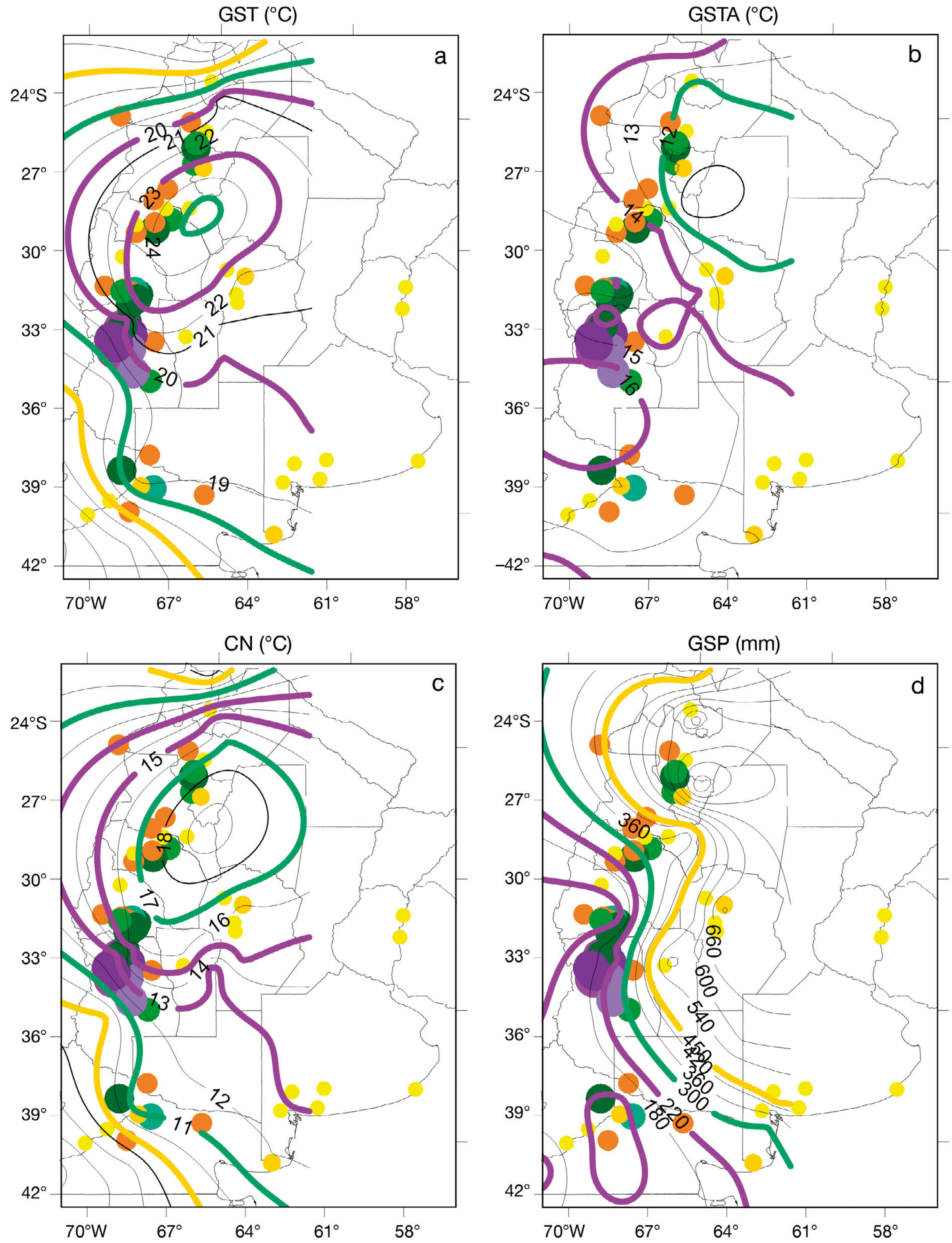

Fig. 5. Climatological mean (2001–2014) bioclimatic indices selected for the unique combined index (UCI). Green, yellow and violet lines denote the limits considered for any given variable (see Table 3 for details). (a) Growing season temperature (GST); (b) growing season mean thermal amplitude (GSTA); (c) cool night index (CN); and (d) growing season precipitation (GSP). Colored dots and location of the meteorological stations as in Fig. 1. Station data was interpolated using the Kriging method

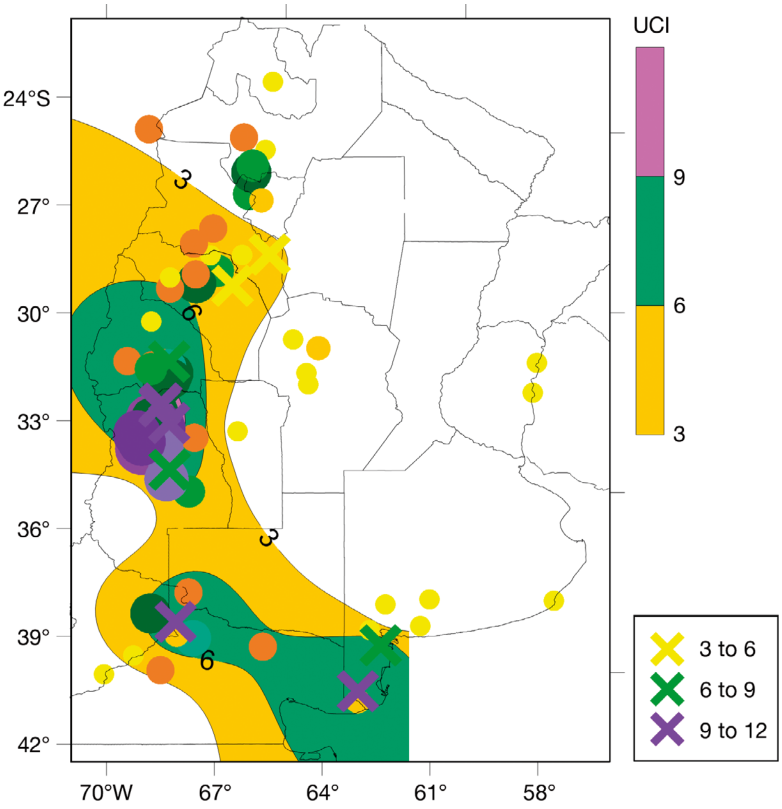

Fig. 6. Spatial distribution of the mean unique combined index (UCI) computed from station data averaged for the period 2001–2014 (shaded areas). Dots denote mean Malbec grape production (MGP) as displayed in Fig. 1. The UCI is unitless. Colored crosses indicate the UCI index calculated for the meteorological stations used. As in Fig. 5, station data was interpolated using the Kriging method. Please refer to Fig. 1 for the location of the meteorological stations

al. (2014a) defined a categorized bioclimatic index that measures the dominant climate conditions based on a set of climatic characteristics. However, their index was not directly associated with the amount of grape or wine production. A similar analysis was performed by Malheiro et al. (2010), who used a composite index that measured the number of years within a given time period that were suitable for grape production, based on whether a set of thresholds involving several bioclimatic indices were fulfilled or not. A similar approach was used by Cabré et al. (2016), who explored the spatial distribution of the GST and GSP indices as simulated by a regional climate model considering the classes according to Hall & Jones (2009). Though these studies assessed suitability, their analyses did not take into account the relationship with actual grape or wine production, a key aspect that has been considered in this study as the basis for defining the regional index.

4. DISCUSSION AND CONCLUSIONS

In this study, an integrated index for MGP suitability in Argentina was defined using a set of bioclimatic indicators accounting for thermal and humidity conditions, with the aim of producing bioclimatic zonification. The main motivation for defining a regional index was a need to evaluate the impact of changing climatic conditions on MGP, which is an important productive activity in the country. Although different indices have already been identified for different viticultural regions of the world (Portugal, Fraga et al. 2014a; Australia, Hall & Jones 2009, among others), there is a lack of studies identifying key bioclimatic indices and their optimum intervals for Malbec grape growth in this region. Accordingly, the aim of this study was to derive a new zoning index for quantifying the suitability of MGP in Argentina.

In order to achieve this goal, the climatic variables that more strongly impact the year-to-year variability of MGP in Mendoza province (where the 52% of the total amount of Malbec grapes are produced) were first identified. GST and GSTA were found to be positively correlated with MGP, suggesting that warmer than normal conditions during the growing season (from October to April) are more favorable for MGP in Mendoza. On the other hand, the CN and GSP indices were found to be negatively correlated with MGP, indicating lower minimum temperatures before harvest (March) and dryer conditions favor MGP. These results allowed identification of the sensitivity of MGP to climatic conditions. The ranges of the selected bioclimatic variables for which MGP from all production locations was above the 66th percentile, between the 66th and 33rd percentile and below the 33rd percentile were identified based on the indices computed at the nearest station for each production location. Hence, for each of the bioclimatic variables selected, individual indices were defined accounting for MGP suitability into 4 categories: non-suitable, low, medium and high suitability with the corresponding scores of 0, 1, 2 and 3, respectively. Finally, these results were integrated into a

UCI, defined as the sum of the individual indices, bearing in mind that the UCI index was set to zero if any of the bioclimatic variables fell into the non-suitability category. The interpretation of the UCI index is simple: if the number of bioclimatic variables falling within the range corresponding to higher than normal MGP conditions is larger it indicates a higher suitability; otherwise, it indicates less favorable climatic conditions for MGP. What is distinctive in this work compared with studies from other viticultural regions of the world is that the classes corresponding to the bioclimatic variables were derived objectively based on the actual co-behavior of the amount of Malbec grapes produced in Mendoza and the climatic conditions that more strongly affect grape production. Moreover, the multi-criteria index derived in this work can be separated into its main components, which would allow identification of the climatic conditions that are more or less favorable to the overall score given by the multi-criteria index.

The UCI index was evaluated in terms of its ability to capture the year-to-year variability of the MGP at Mendoza and also in terms of its ability to capture the spatial distribution of MGP in Argentina. It was found that the time series of UCI was significantly correlated with the time series of MGP in Mendoza, suggesting that the UCI index is an adequate tool for identifying more or less suitable climatic conditions for MGP. The spatial distribution of the mean UCI index was also able to reproduce the areas where Malbec grapes are produced, in agreement with actual MGP distribution. Moreover, the index quantifies suitability so that it is able to indicate not only where the climate conditions are suitable for MGP, but also where this suitability is higher or lower. This is another important added value of the UCI index, compared with other categorized indices defined in the literature (e.g. Tonietto & Carbonneau 2004, Fraga et al. 2014a).

The interpretation of the UCI index has both a climatic and viticultural dimension. The climatic dimension is represented by its magnitude, indicating how favorable the climatic conditions are for the production of Malbec. The viticultural dimension is based on the influence of 2 of the bioclimatic indices included in the definition of UCI, which are usually related to wine quality: GST and CN. These 2 indices affect vines, grapes and the quality and style of wine. The GST provides the basis for placing latitudinal boundaries on viticulture zones (Jones 2006) and is an essential factor in grapevine maturation (Gladstones 2011). Its importance lies in that it defines optimum climatic ranges for the development of a given variety, and is a useful indicator of the requirements of different varieties to properly ripen in terms of sugar accumulation in the berries. On the other hand, the CN index refers to the color and aroma of both grapes and wine (Kliewer & Torres 1972) and provides a complementary idea of the thermal regime in the ripening stage of grapes.

It is important to note that bioclimatic indices usually perform better when they are computed on a daily basis (e.g. Malheiro et al. 2010, Santos et al. 2012, Gu 2016). Using monthly data may smooth out the occurrence of daily extremes, which strongly affect grapes, and thus may limit the quality of the results. Another caveat in the methodology is that empirically based models, as the one we are presenting here, describe the relationship between predictors (in this case several bioclimatic indices) and productivity, accounting for the fact that climate (e.g. climate indices such as accumulated rainfall or average temperature of a certain month) is one of the key factors influencing yield quantity and quality (Jones et al. 2005). As such, empirical models need a limited amount of input data to produce an output, but cause−effect mechanisms between climate and yield are not explicitly described. This may limit the applicability of this approach to the specific regions or varieties for which the relationships were calibrated.

The region where this study was focused is characterized by very complex topographic features encompassing a wide range of altitudes, with vineyards located from 450−1500 m. The study was focused on broad regional climatic features and accordingly, on regional zoning, without going in too much local detail. First of all, the station data we used did not have sufficient spatial resolution to address the dependence on local versus regional features. Data from regular weather stations are not always located in proximity to the major vineyards. Moreover, the MGP data we used did not come from a single vineyard, but from bulk values of several departments from each province. Therefore, the zoning exercise described in this study is intended to account for the regional scale features. Local features accounting for the relationship between vineyard locations and altitude have not been considered.

Finally, the UCI index defined here represents a useful tool to evaluate the impact of changing climate conditions on MGP, both in terms of its temporal behavior but also in terms of identifying potential changes in the spatial distribution of suitability for MGP, which will be a subject for future studies. Hereafter, it is important to recall that one of the aims of deriving the zoning index is to assess to what extent climate change may impact MGP in Argentina. Moreover, the UCI index can also be used as a prediction tool at the seasonal scale. Though it is likely that other bioclimatic variables, such as the number of hours of sunshine, air humidity, evapotranspiration and water balance may also impact grape production, the availability of these variables may be difficult to guarantee when using climate model data for both present and future climate conditions. The next step will be to evaluate the capability of the models to reproduce suitable areas, and then to assess future changes. As already known, modeled variables are far from being error-free, and bias-correction methods are becoming a common strategy, mainly applied to precipitation and temperature. For all these reasons, the definition of the index has been kept as simple as possible in terms of the variables more commonly available from climate models (monthly mean temperature and precipitation) in order to compute the index with climate model data.

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LITERATURE CITED

Agosta E, Canziani P, Cavagnaro M (2012) Regional climate variability impacts on the annual grape yield in Mendoza, Argentina. J Appl Meteorol Climatol 51:993–1009

Anderson JD, Jones GV, Tait A, Hall A, Trought MC (2012) Analysis of viticulture region climate structure and suitability in New Zealand. J Int Sci Vigne Vin 46:149–165

Cabré MF, Quénol H, Nuñez M (2016) Regional climate change scenarios applied to viticultural zoning in Mendoza, Argentina. Int J Biometeorol 60:1325–1340

Carbonneau A, Riou C, Guyon D, Riom J, Schneider C (1992) Agrométéorologie de la vigne en France. Office des Publications Officielles des Communautés Européennes, Luxembourg

Diffenbaugh NS, Scherer M (2013) Using climate impacts indicators to evaluate climate model ensembles: temperature suitability of premium winegrape cultivation in the United States. Clim Dyn 40:709–729

Fanzone M, Peña-Neira A, Jofré V, Assof M, Zamora F (2010) Phenolic characterization of Malbec wines from Mendoza Province (Argentina). J Agric Food Chem 58: 2388–2397

Fraga H, Malheiro AC, Moutinho-Pereira J, Jones GV, Alves F, Pinto JG, Santos JA (2014a) Very high resolution bioclimatic zoning of Portuguese wine regions: present and future scenarios. Reg Environ Change 14:295–306

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2014b) Climate factors driving wine production in the Portuguese Minho region. Agric Meteorol 185:26–36

Fraga H, Santos JA, Malheiro AC, Oliveira AA, Moutinho-Pereira J, Jones GV (2016) Climatic suitability of Portuguese grapevine varieties and climate change adaptation. Int J Climatol 36:1–12

Gladstones J (2011) Wine, terroir and climate change. Wakefield Press, Kent Town

Gu S (2016) Growing degree hours — a simple, accurate, and precise protocol to approximate growing heat summation for grapevines. Int J Biometeorol 60:1123–1134

Hall A, Jones GV (2009) Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. Aust J Grape Wine Res 15:97–119

Huglin P (1983) Possibilités d'appréciation objective du milieu viticole. Bull OIV 56:823–833

INV (Instituto Nacional de Vitivinicultura) (2016) Informe Variedad Malbec. Departamento de estadística y estudios de Mercado, Mendoza

Irimia LM, Patriche CV, Quénol H (2014) Analysis of viticultural potential and delineation of homogeneous viticultural zones in a temperate climate region of Romania. J Int Sci Vigne Vin 48:145–167

Jones GV (2006) Climate and terroir: impacts of climate variability and change on wine. In: Macqueen RW, Meinert LD (eds) Fine wine and terroir — the geoscience perspective. Geoscience Canada Reprint Series 9, Geological Association of Canada, St. John's

Jones GR, Davis 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 GV, White MA, Cooper OR, Storchmann K (2005) Climate change and global wine quality. Clim Change 73: 319–343

Jones GV, Duff AA, Hall A, Myers JW (2010) Spatial analysis of climate in winegrape growing regions in the western United States. Am J Enol Vitic 61:313–326

Kliewer WM (1973) Berry composition of *Vitis vinifera* cultivars as influenced by photo and nycto-temperatures during maturation. J Am Soc Hortic Sci 2:153–159

Kliewer WM, Torres RE (1972) Effect of controlled day and night temperatures on grape coloration. Am J Enol Vitic 2:71–77

Lorenzo MN, Taboada JJ, Lorenzo JF, Ramos AM (2013) Influence of climate on grape production and wine quality in the Rias Baixas, north-western Spain. Reg Environ Change 13:887–896

Malheiro AC, Santos JA, Fraga H, Pinto JG (2010) Climate change scenarios applied to viticultural zoning in Europe. Clim Res 43:163–177

Montes C, Pérez-Quezada JF, Peña-Neira A, Tonietto J (2012) Climatic potential for viticulture in central Chile. Aust J Grape Wine Res 18:20–28

Moriondo M, Bindi M, Fagarazzi C, Ferrise R, Trombi G (2011) Framework for high-resolution climate change impact assessment on grapevines at a regional scale. Reg Environ Change 11:553–567

Moriondo M, Jones GV, Bois B, Dibari C, Ferrise R, Trombi G, Bindi M (2013) Projected shifts of wine regions in response to climate change. Clim Change 119:825–839

Moriondo M, Ferrise R, Trombi G, Brilli L, Dibari C, Bindi M (2015) Modelling olive trees and grapevines in a changing climate. Environ Model Softw 72:387–401

Myburgh PA (2003) Responses of *Vitis vinifera* L. cv. Sultanina to water deficits during various pre- and post-harvest phases under semi-arid conditions. S Afr J Enol Vitic 24: 25–33

OIV (International Organisation of Vine and Wine) (2015) Statistics of the International Organisation of Wine. www.oiv.int/es/bases-de-datos-y-estadisticas/estadisticas (accessed 29 Sept 2016)

Quenol H, Madelin M, Loussert P, Corgne S Grassin M (2015) Influence du climat local sur la viticulture dans la Province de Mendoza (Argentine). Actes du 28ème colloque de l'AIC, Liège

Ramos MC, Martínez-Casasnovas JA (2010) Effects of precipitation patterns and temperature trends on soil water available for vineyards in a Mediterranean climate area. Agric Water Manage 97:1495–1505

Ramos MC, Jones GV, Martínez-Casasnovas JA (2008) Structure and trends in climate parameters affecting winegrape production in northeast Spain. Clim Res 38: 1–15

Riou C, Carbonneau A, Becker N, Caló A and others (1994) Le déterminisme climatique de la maturation du raisin: application au zonage de la teneur en sucre dans la Communauté Européenne. Office des Publications Officielles des Communautés Européennes, Luxembourg

Santos JA, Malheiro AC, Karremann MK, Pinto JG (2011) Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. Int J Biometeorol 55:119–131

Santos JA, Malheiro AC, Pinto JG, Jones GV (2012) Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. Clim Res 51:89–103

Santos JA, Grätsch SD, Karremann MK, Jones GV, Pinto JG (2013) Ensemble projections for wine production in the Douro Valley of Portugal. Clim Change 117:211–225

Soar CJ, Sadras VO, Petrie PR (2008) Climate-drivers of red wine quality in four contrasting Australian wine regions. Aust J Grape Wine Res 14:78–90

Tonietto J, Carbonneau A (2004) A multicriteria climatic classification system for grape-growing regions worldwide. Agric Meteorol 124:81–97

van Leeuwen C, Darriet P (2016) The impact of climate change on viticulture and wine quality. J Wine Econ 11: 150–167

Vasconcelos MC, Greven M, Winefield CS, Trought MCT, Raw V (2009) The flowering process of *Vitis vinifera*: a review. Am J Enol Vitic 60:411–434

Vaudour E, Shaw AB (2005) A worldwide perspective on viticultural zoning. S Afr J Enol Vitic 26:106–115

Winkler A, Cook AJ, Kliewere WM, Lider LA (1974) General viticulture, 4th edn. University of California Press, Berkley, CA

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