iVES OENO One vine & wine

DOI: https://doi.org/10.20870/oeno-one.2024.58.4.8196

OPEN ACCESS

15TH INTERNATIONAL TERROIR CONGRESS MENDOZA, ARGENTINA

ORIGINAL RESEARCH ARTICLE

Assessment of Albariño (*Vitis vinifera* sp.) plasticity to local climate in the Atlantic eastern coastal terroir of Uruguay

Mercedes Fourment[1], Ramiro Tachini[1], Valérie Bonnardot[2], Cassandra Collins[3]

[1] Universidad de la República, Facultad de Agronomía, Av. E. Garzón 780, Montevideo, Uruguay
[2] Université Rennes 2, UMR CNRS 6554 LETG, Place du Recteur Henri Le Moal, Rennes, France
[3] University of Adelaide, School of Agriculture, Food and Wine, Waite Research Institute, PMB 1 Glen Osmond, 5064 South Australia, Australia

This article is published in cooperation with the XVth International Terroir Congress, 18-22 November 2024, Mendoza, Argentina.

Guest editors: Federico Berli, Jorge Prieto and Martín Fanzone.

ABSTRACT

Plasticity is typically used in biology to describe the ability of an organism to adapt to changes in its environment. Within a viticulture production system under similar management practices, studying the plasticity of a specific cultivar under different local climatic conditions can enhance our understanding of the grape typicity and, consequently, the wine style of a region. This work aims to assess the performance of Albariño vines grown in different mesoclimates within the emerging wine region along Uruguay's Atlantic coast. The study was conducted in a commercial vineyard in Garzón, Maldonado Department, a key location in this developing wine region. Temperature sensors were installed in each of the four Albariño plots, situated in two contrasting topographic positions relative to Atlantic Ocean exposure, to assess mesoclimate and the ocean's influences on grapevine plasticity. Agronomic measurements were taken to assess the performance of Albariño under the local climatic conditions. The multivariate analysis of yield and berry composition variables with ocean exposure and seasonal climate has identified three key findings: 1) the Albariño cultivar has shown strong potential for cultivation in eastern Uruguay due to its favourable agronomic and oenological performance, 2) vineyard ocean exposure has a greater effect on berry composition at harvest than on yield, contributing 70.7 % and 63.4 % of the total variability, respectively as observed from the Principal Component Analysis, 3) the correlations between berry composition and ocean exposure are stronger under warmer and drier conditions. Understanding the plasticity of Albariño under different local climatic conditions is valuable for sustainable production systems, provided both production and high quality are maintained. This study highlights the importance of selecting appropriate cultivars and understanding the local climate for the future success of vineyards.

KEYWORDS: Terroir 2024, climate variability, plasticity, Albariño, Atlantic Ocean, South America

*correspondence: mfourment@fagro.edu.uy

Associate editor: Federico Berli

Received: 15 June 2024

Accepted: 14 October 2024

Published: 4 November

This article is published under the **Creative Commons licence** (CC BY 4.0).

Use of all or part of the content of this article must mention the authors, the year of publication, the title, the name of the journal, the volume, the pages and the DOI in compliance with the information given above.

INTRODUCTION

Growing concerns about grapevine adaptability to climate change highlight the need for a deeper understanding of local environmental factors and their effects on grape physiology, berry composition, and wine quality to effectively address these challenges (Fourment *et al.*, 2024). The impact of climate variability on viticulture is a critical area of study, particularly in regions like eastern Uruguay where environmental conditions fluctuate significantly (Hareau *et al.*, 1999). Numerous studies have demonstrated the impact of spatial climate variability on vine physiology and metabolism, and grape and wine quality in different wine regions such as Loire Valley (Bonnefoy *et al.*, 2013), Burgundy (Madelin *et al.*, 2014) and Bordeaux (de Rességuier *et al.*, 2020; Pieri *et al.*, 2022) in France, Galicia (Blanco-Ward *et al*., 2007), Rioja (Ramos and Martínez de Toda, 2021), and Ribera del Duero in Spain (Ramos *et al.*, 2015), Northeastern Slovenia (Vršič *et al*., 2014), Serbia (Ruml *et al.*, 2016), South Tyrol in Italy (Ferretti, 2021), Santa Catarina in Brazil (Falcao *et al.*, 2010), various wine regions in Australia (Hall and Jones, 2010), Stellenbosch in South Africa (Carey *et al.*, 2003) and Lavaux in Switzerland (Rienth *et al.*, 2020).

In Uruguay, previous studies have highlighted the influence of temporal climate variability, particularly concerning precipitation patterns, on various wine regions (Fourment *et al.*, 2013; Ferrer *et al.*, 2020; Tachini *et al.*, 2023a). At a large scale, the equatorial Pacific El Niño-Southern Oscillation (ENSO) is a major driver of regional climate interannual variability in Uruguay, and South America generally. ENSO periodically affects weather patterns with varying regional impacts depending on its phase: El Niño (positive) and La Niña (negative). In Southeastern South America, including Uruguay, El Niño events typically lead to wet conditions (especially during spring), while La Niña events are associated with dry conditions (Barreiro, 2009; Penalba and Rivera, 2016). The regional climatic impacts of ENSO affect agricultural productivity as shown in America (Anderson *et al.*, 2017) or central South America (Arias *et al.*, 2023). Among the most important annual crops planted in the Americas, such as maize, soybean and wheat, the ENSO phenomena accounts for approximately 72 %, 30 % and 57 % of their production variability, respectively, which could pose risks to food security (Anderson *et al.*, 2017). Research has shown varied impacts of ENSO events on viticulture across South America. For example, the 1997 El Niño event led to early harvests and low yields in Peru (Yzarra *et al*., 2015). Similarly, recent studies in Brazil found that bioclimatic indices for viticulture correlate with ENSO phases, showing reduced yield and sugar content during El Niño events (Lemos Kaltbach *et al*., 2022; Lemos Kaltbach *et al*., 2024). In contrast, the 2023 La Niña event in Uruguay resulted in lower yields but higher sugar content (Fourment and Piccardo, 2023). Additionally, Verdugo-Vazquez *et al.* (2023) highlighted the influence of the Pacific anticyclone on viticulture in Chile based on a 30-year climatic analysis. For Uruguay, Rusticucci and Renom (2008) observed a warming trend in night temperatures from 1960 to 2002, correlating with sea surface temperature anomalies in the Pacific Ocean (ENSO). This warming could also impact viticulture and the development of wine aroma and flavour. Future climate change scenarios for Uruguay predict higher temperatures, increased extreme heat events (likely more frequent during winter), and reduced cold spells. Warm nights are projected to increase even more than warm days, while rainfall is predicted to intensify, particularly in summer and autumn, potentially leading to more floods (Intergovernmental Panel on Climate Change, 2023).

On the other hand, spatial variability in climate, particularly due to the proximity to the Atlantic Ocean, plays a crucial role in shaping vineyard conditions. Vineyards closer to the ocean benefit from the cooling effects of sea breezes during peak daily temperatures, reducing thermal stress, especially during ripening in warm climates. For example, Bonnardot *et al.* (2005) observed that the sea breezes in the Stellenbosch district of South Africa, lowered vineyard temperatures by 3 to 6 °C during the hot hours of February, mitigating heat stress during ripening. Similarly, Fourment *et al.* (2014) recorded a temperature decrease between 2 to 4 °C in the La Plata River basin in Uruguay. Both studies also demonstrated the impact of this local phenomenon on grape aromas (Carey *et al.*, 2003) and anthocyanins (Fourment *et al.*, 2017).

In the last fifteen years, Uruguay's exploration of new viticultural terroirs has prompted winegrowers to establish vineyards in the cooler eastern part of the country, significantly influenced by the Atlantic Ocean. This emerging wine region, encompassing the Maldonado and Rocha Departments, has expanded from 308 ha to 432 ha over the past decade, now comprising 7.3 % of the nation's total vineyard area (Instituto Nacional De Vitivinicultura, 2024). Despite a national decline in vineyard surface area, the growth in this coastal Atlantic region underscores a strategic shift towards leveraging its unique climatic and geographical advantages.

In this complex challenging context with multiscale interactions, a multi-faceted strategy for adapting viticulture to climate change is essential. This includes considering alternative cultivars or changing geographic locations, as discussed by Fourment *et al.* (2020) and Rogiers *et al.* (2022), facilitating a broader range of cultivation opportunities.

Phenotypic plasticity refers to an organism's capacity to modify its physiology and morphology in response to environmental changes (Schlichting, 1986). For grapevines, this adaptability is crucial for coping with varying environmental conditions and stressors. Alongside local adaptation, phenotypic plasticity, helps plants adjust to environmental variability and acclimate (Liu *et al.*, 2016), thereby allowing wider distribution for cultivation. Grapevine plasticity to different environmental conditions, including spatial and seasonal climates and soil types, is well-documented (Sadras *et al.*, 2009; Gladstone, 2015). Understanding a grape cultivar's plasticity can provide essential insights for vineyard management practices,

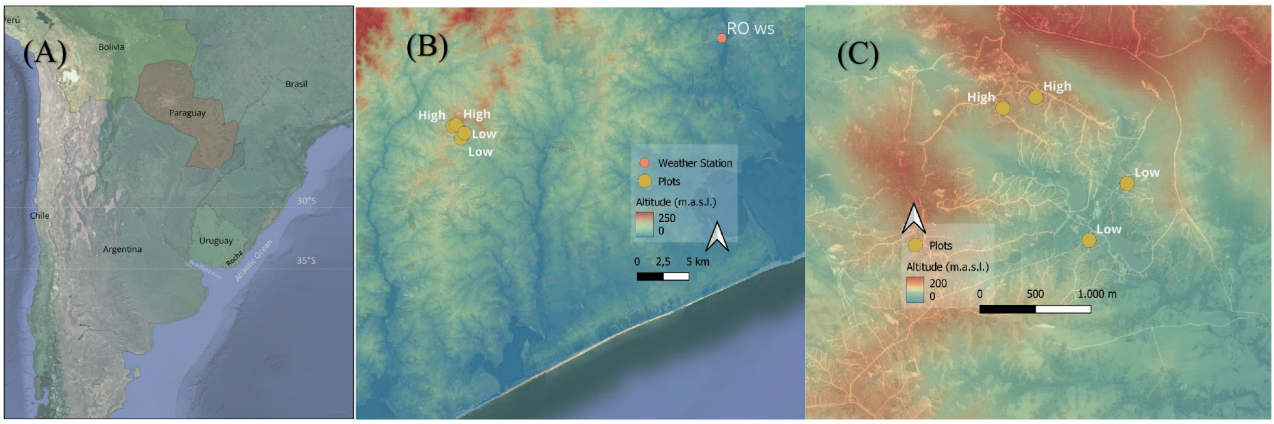


FIGURE 1. Location of Uruguay in South America (A); location of the Rocha Weather Station from INUMET and the four plots at the different exposure to the Atlantic Ocean (High and Low exposition based on contrasting topographic situations) (B); zoom on the four plots (High and Low exposition) and the land's topography (C).

enabling viticulturists to optimise the terroir expression and achieve consistent wine quality and distinctiveness (typicity) in different environmental conditions.

Gavrilescu and Bois (2016) analysed the climate plasticity of Chardonnay, the fifth most widely planted cultivar in the world. Their study highlighted the diverse climates where this variety is grown resulting in high and award-winning wines and, thus, its adaptive potential for addressing climate change. Young *et al.* (2016) discussed phenotypic plasticity in another white cultivar, Sauvignon blanc, showing that plastic/non-plastic metabolite responses could be further classified to identify metabolites that were developmentally controlled and/or responded to the treatment predictably. Their study demonstrates that Sauvignon blanc berries exhibit a degree of plasticity within their secondary metabolites at different microclimate exposures, with notable oxidative responses in final berry compounds such as increased norisoprenoids and monoterpenes. Albariño, a white grapevine cultivar from Galicia, Spain, has shown significant potential in Uruguay for producing fine wines, largely due to its ability to maintain both productivity and quality even in wet seasons. This has established Albariño as the second most important high-quality white variety in Uruguay, after Sauvignon blanc (Instituto Nacional De Vitivinicultura, 2024). However, further scientific research is necessary to confirm this practical experience.

In this context, the study contributes to improving our understanding of the plasticity of Albariño vines to local climate conditions, focusing on vineyards grown under consistent management practices in the emerging eastern wine region of Uruguay.

MATERIALS AND METHODS

1. Site and experiment details

The study was developed in a commercial vineyard in an emerging wine region on the Atlantic side of southeastern Uruguay (Garzón, located in the Maldonado Department). The area's climate is classified as temperate, with temperate nights and moderated drought, corresponding to the ISA1IHA3IFA2, climatic group according to the "Multicriteria Climatic Classification" method for vineyards (Ferrer *et al.*, 2007; adapted from Tonietto and Carbonneau (2004)). The grape ripening period in southeastern Uruguay is characterised by temperate-maximum temperatures, and the daily mean temperature during the growing season is 18.9 °C (Fourment *et al.*, 2020).

Four temperature sensors (Tinytag data loggers, Gemini, UK) were installed in plots of Albariño in contrasted topographical situations, which were classified into two classes, i.e., High (H) and Low (L) exposure to the Atlantic Ocean based on spatial climatic differences (Table 1 as mentioned in Tachini *et al.*, 2023a for greater details) (Figure 1B,C). The four plots have the same type of soil, classified as Brunosol by the National Classification. This study shows results over five consecutive growing seasons from the 1st of September to the 1st of March of 2018–2019 to 2022–2023. This refers to the year of harvest, especially from 2019 for the 2018–2019 study season, up to 2023 for the final study season of 2022–2023.

2. Climate assessment

Seasonal variability in temperatures and precipitation in the region was evaluated using daily data obtained from the Rocha weather station (Figure 1B), provided by the Meteorology National Institute (INUMET) network adhering to the World Meteorological Organization (WMO) standards. Regional climate variability was evaluated during the growing seasons over the five consecutive vintages (2019 to 2023). The climatic indicators used were precipitation during the growing season (PP), precipitation during ripening (January and February), number of days with precipitation (NPP), average growing season temperature (Jones, 2006), thermal amplitude during summer (January and February) (THA), growing degree days from 1st September to 28th February (GDD) (Winkler, 1974), cool night index as mean minimum temperature of February (CNI) and the numbers of days with temperatures above 35 °C (ND35).

Spatial variability of temperature within the vineyard was further assessed using hourly temperature data measured by temperature sensors (Tinytag dataloggers, Gemini, UK) through the calculation of bioclimatic indices for each season, at each plot, such as GDD; THA; CNI; season minimum temperature (TN); season maximum temperature (TX); number of days with temperatures above 30 °C (ND30); number of days with temperatures above 35 °C (ND35); maximum temperature in January (TXJan); minimum temperature in January (TNJan); maximum temperature in November (TXNov); minimum temperature in November (TNNov). To investigate the influence of sea breezes, we analysed the number of hours with temperature decreases of varying intensities (0.5 °C and 1.0 °C) during peak temperatures between 11:00 and 16:00 Local hour (LH) as mentioned in Fourment *et al.* (2014). Thus, the variables Freq.H-0.5 and Freq.H-1 represent the temperature drop of 0.5 °C or 1 °C during heat waves. We considered heat waves as a period of three or more consecutive days with a maximum temperature of 32.3 °C (De Mello and Renom, 2024). Yearly climatic variables were used to study the grapevine's response to seasonal climate variability. The climatic variables obtained for each plot were used to assess the impact of spatial temperature variability over the vintage.

3. Albariño performance assessment

According to PlantGrape (2024), Albariño is a moderately vigorous variety with a horizontal growth habit that requires careful trellising. It is not highly productive and benefits from cane pruning. Well-suited to acidic, granite, and sandy soils, Albariño is relatively tolerant to *Botrytis* rot (PlantGrape, 2024) and produces elegant wines with good acidity. Consequently, Albariño cultivation in Uruguay has increased by 24 % over the past five years, now comprising 1.6 % of the country's vineyards (Instituto Nacional De Vitivinicultura, 2024).

In this study, we analysed four plots of high-quality Albariño grapevines planted in 2009 (13 years old), which were trained to a vertical shoot positioned (VSP) training system and pruned using the double Guyot method. The planting density is 2 m between rows and 1 m between vines resulting in 5,000 vines per ha. Yield components were assessed for each plot using two replicates of seven contiguous vines. For each vine, we assessed the total number of clusters, yield per vine (kg/vine), yield per vine without *Botrytis* (kg/vine) (rot incidence), berry weight (mean value of the 250 samples of berries, the description is below), pruning weight (kg/vine) in winter, and Ravaz Index (Fruit weight/kg per pruning weight/kg) (Ravaz, 1911).

During the ripening period, berry samples were collected weekly, as outlined by Carbonneau *et al.* (1991). Grape berry composition measures undertaken were sugar content (SC) (g/l) by refractometry, total acidity (TA) (g H_2SO_4/l) by titration, and pH by potentiometry, according to the O.I.V. protocol (1990). To analyse phenolic potential (Total Phenolic Index of grapes), the Glories and Agustin (1993) protocol was followed with a Shimadzu UV-1240 Mini (Shimadzu, Japan) spectrophotometer. These variables are important to assess fruit quality and winemaking potential (González-Néves *et al.*, 2010).

4. Statistical analyses

Univariate statistical analysis (ANOVA) was used to evaluate every climate and agronomic variable to determine the influence of season and exposure to the Atlantic Ocean at different confidence levels. We used two variation factors: plot exposure to the Atlantic Ocean named as plot site—PS (H and L exposure to the Atlantic Ocean) to assess local climate impact, year—Y (2019 to 2023 seasons) to assess seasonal impact; and we calculated the interaction PS × Y. The variance percentage was calculated for each variable between consecutive years. To analyse the plasticity of Albariño through the relationships between local climate and Albariño agronomic performances and oenological potential, a Pearson correlation matrix was made. Multivariate statistical analysis was performed to elucidate correlations between climate and agronomic data. Principal component analysis (PCA) was conducted to analyse the dataset to differentiate the plot's location and season effect. To demonstrate relationships between yield components and berry composition variables over the five seasons, plot location and season were analysed separately to identify the general variability effects. The statistical analysis was performed using Infostat® and OriginLab® programs.

TABLE 1. Climatic indicators from the Rocha weather station, Uruguay during the 2019 to 2023 growing seasons.

Growing season/Variables	2019	2020	2021	2022	2023	Average
PP *	933	579	405	792	214	584
PP ripening .	283	85	218	319	50	191
NPP *	75	53	59	58	31	55.2
TM	18.6	18.3	17.8	18.8	18.5	18.4
THA*	11.0	12.7	11.2	12.2	11.0	11.61
GDD*	1694	1655	1557	1737	1900	1709
CNI	17.8	17.1	16.8	18.4	18.0	17.6
N35*	4	11	2	8	20	9.0

*Statistical differences between years ($\alpha \leq 0.005$). Abbreviations: PP = Precipitation, PP ripening = Precipitation in the ripening period, NPP = Number of days with precipitation, TM = Average temperature of the period, THA=Thermal amplitude during summer, GDD = Growing degree days, CNI = Cool night index, and ND35 = Number of days with temperatures above 35 °C.

RESULTS

1. Temporal and spatial climate variability during 5 growing seasons

The region's climate variability was strongly associated with precipitation patterns and temperature-high extremes (Table 1). On average, the growing seasons received 584 mm of rainfall over the five-year period. Seasons 2019 and 2022 received greater rainfall than the average during the season (+348 and +208 mm, respectively) and the ripening period (+92 and +128 mm, respectively). Only 2019 had a greater number of rain days. During the five seasons, the thermal indicators that showed statistical differences were THA, GDD and N35. 2020 and 2022 had the highest values in THA during ripening (1.09 and 0.59 °C more than the average, respectively), while in terms of heat accumulation 2023 was the season with higher GDD values (191 °C more than the average). On average, Rocha Weather Station showed 9 days with temperatures above 35 °C and 2.2 days in 2023.

The average values of the thermal indices calculated using data from the sensors installed in the vineyards showed a significant season effect, as well as a significant plot site effect for 8 of 13 indicators (Table 2).

Within the five growing seasons, 2023 was the hottest and driest, during which the greatest differences between plot locations were found (spatial variability). For example, under the warmest seasonal conditions of the study period, the impact of sea breeze was greater on plots exposed to the Atlantic Ocean, recording 6.5 hours more than others with a temperature drop at midday (Table 2). Other bioclimatic indices were influenced by ocean exposition: minimum temperatures, such as the Cool Night Index, minimum temperature during the growing season, January minimum temperature, and November minimum temperature (Table 2).

TABLE 2. Climatic indicators during the 2019 to 2023 growing seasons comparing High (H) and Low (L) exposure to the Atlantic Ocean (Plot Site—PS), the year effect (Y) and the interaction (PS × Y). Values in brackets represent the variance percentage of the variable of the year compared to the previous one. (Part 1/2).

Variables	Sites	2019	2020	2021	2022	2023	Mean
GDD	H	1655 b	1718 (4 %)	1661 b (–3 %)	1745 (5 %)	1761 (1 %)	1708 b
	L	1628 a	1726 (6 %)	1573 a (–9 %)	1722 (9 %)	1694 (–2 %)	1667 a
	PS	***	ns	**	ns	ns	***
	Y						***
	PS × Y						ns
THA	H	11.5	12.6 a (10 %)	11.3 (–10 %)	10.3 (–9 %)	11.4 (11 %)	11.4 a
	L	12.4	14.6 b (18 %)	12.7 (–13 %)	11.8 (–7 %)	13.1 (11 %)	12.8 b
	PS	ns	**	ns	ns	ns	***
	Y						***
	PS × Y						ns
CNI	H	16.3	16.4 b (1 %)	17.2 b (5 %)	16.7 (–3 %)	17.6 (5 %)	16.9 b
	L	15.6	15.4 a (–1 %)	16.0 a (4 %)	15.7 (–2 %)	16.9 (8 %)	15.9 a
	PS	ns	*	*	ns	**	***
	Y						***
	PS × Y						ns
TN	H	16.3	13.4 (–18 %)	13.2 b (–1 %)	14.4 (9 %)	14.3 b (–1 %)	14.3 b
	L	15.6	13.4 (–14 %)	11.7 a (–13 %)	13.4 (15 %)	13.0 a (–3 %)	13.4 a
	PS	ns	ns	*	ns	***	***
	Y						***
	PS × Y						*
TX	H	27.5	25.7 (–7 %)	24.8 (–4 %)	24.7 a (0 %)	24.9 (1 %)	25.5 a
	L	27.6	25.8 (–7 %)	25.2 (–2 %)	25.4 b (1 %)	25.5 (0 %)	25.9 b
	PS	ns	ns	ns	**	ns	***
	Y						***
	PS × Y						ns

TABLE 2. Climatic indicators during the 2019 to 2023 growing seasons comparing High (H) and Low (L) exposure to the Atlantic Ocean (Plot Site—PS), the year effect (Y) and the interaction (PS × Y). Values in brackets represent the variance percentage of the variable of the year compared to the previous one. (Part 2/2).

ND30							
	H	22.9	55.0 (140 %)	35.0 (–36 %)	36.0 a (3 %)	45.0 (25 %)	40.0 a
	L	28.5	58.5 (105 %)	39.5 (–32 %)	42.00 b (6 %)	52.5 (25 %)	44.2 b
	PS	ns	ns	ns	**	ns	**
	Y						***
	PS × Y						ns
ND35							
	H	6.5	5 (–23 %)	1.5 (–70 %)	4.5 a (200 %)	3.5 (–22 %)	4.2
	L	3.5	4 (14 %)	1.0 (–75 %)	7.3 b (630 %)	4.5 (–38 %)	4.36
	PS	ns	ns	ns	*	ns	ns
	Y						***
	PS × Y						**
TXJan							
	H	28.4	29.8 (5 %)	29.5 (–1 %)	29.7 (1 %)	30.0 (1 %)	29.5
	L	28.4	29.2 (3 %)	29.5 (1 %)	30.2 (2 %)	30.5 (1 %)	29.6
	PS	ns	ns	ns	ns	ns	ns
	Y						***
	PS × Y						ns
TNJan							
	H	17.6 b	15.6 (–11 %)	16.9 b (8 %)	17.7 (5 %)	18.1 b (2 %)	17.3 b
	L	17.0 a	15.7 (–8 %)	15.6 a (–1 %)	18.3 (17 %)	16.7 a (–9 %)	16.6 a
	PS	**	Ns	***	ns	**	***
	Y						***
	PS × Y						*
TXNov							
	H		25.6	23.7 (–7 %)	23.1 b (–3 %)	24.1 (4 %)	24.1
	L		26.3	24.4 (–7 %)	23.8 a (–2 %)	24.8 (4 %)	24.8
	PS		ns	ns	0.02	ns	ns
	Y						***
	PS × Y						ns
TNNov							
	H		14.5 b	12.6 b (–13 %)	13.0 b (3 %)	13.8 b (6 %)	13.5 a
	L		13.6 a	10.7 a (–21 %)	10.7 a (0 %)	12.3 a (15 %)	11.8 b
	PS		***	**	*	***	**
	Y						***
	PS × Y						*
Freq.H-0.5							
	H	50.5	46 (–9 %)	49.5 (8 %)	50.5 (2 %)	101.5 a (101 %)	59.6
	L	42.5	42 (–1 %)	52.5 (25 %)	48 (–9 %)	82 b (71 %)	37.2
	PS	ns	ns	ns	ns	*	ns
	Y						***
	PS × Y						ns
Freq.H-1							
	H	28	29.5 (5 %)	35 (19 %)	32 (–9 %)	61.5 a (92 %)	53.4
	L	25.5	30 (18 %)	31.5 (5 %)	33.5 (6 %)	55 b (64 %)	35.1
	PS	ns	ns	ns	ns	**	ns
	Y						***
	PS × Y						*

Statistical significance: *p < 0.01 **p < 0.005 ***p < 0.001. Abbreviations mean GGD = Growing Degree Days; THA = thermal amplitude in summer; CNI = cool night index; TN = season minimum temperature; TX = season maximum temperature; ND30 = number of days with temperatures above 30 °C; ND35 = number of days with temperatures above 35 °C; TXJan = maximum temperature in January; TNJan = minimum temperature in January; TXNov = maximum temperature in November; TNNov = minimum temperature in November; Freq.H-0.5 = frequency in the number of hours with a temperature drop of 0.5 °C; Freq.H-1 = frequency in the number of hours with a temperature drop of 1 °C.

2. Yield and berry composition

Albariño yields were, on average, 1.7 kg per vine, with similar berry weight between years (1.3 g) and similar cluster number (19.2 clusters per vine on average). The yields with and without *Botrytis* rot achieved in the plots were similar, showing a low rot incidence in this cultivar. Only in 2022 was *Botrytis* rot observed on grapes, resulting in yield losses (Table 3).

Differences in yield components between plot sites (High and Low exposure to the Atlantic Ocean, named H and L) were only observed in some seasons. Specifically, yield per vine was only statistically different in 2021, when H presented 0.72 kg per vine more than L, and cluster number in 2022, when L had 7.6 more clusters than H. Yield without rot was significantly different in 2021, when H plots had a higher rot

TABLE 3. Yield components during the 2019 to 2023 growing seasons comparing High (H) and Low (L) exposure to the Atlantic Ocean (Plot Site—PS), the year effect (Y) and the interaction between year and plot site (PS × Y). Values in brackets represent the variance percentage of the variable of the year compared to the previous one.

Variables	Sites	2019	2020	2021	2022	2023	Mean
Yield	H	1.47	2.39 (63 %)	2.28 b (–5 %)	1.06 (–54 %)	1.69 (59 %)	1.79
	L	1.79	1.71 (–4 %)	1.56 a (–9 %)	1.28 (–18 %)	1.95 (52 %)	1.71
	PS	ns	ns	*	ns	ns	
	Y						***
	PS × Y						*
Berry weight	H	1.15	1.28 (11 %)	1.61 (26 %)	1.25 (–22 %)	1.37 (10 %)	1.3
	L	1.19	1.27 (7 %)	1.58 (24 %)	1.26 (–20 %)	1.33 (6 %)	1.3
	PS	ns	ns	ns	ns	ns	ns
	Y						***
	PS × Y						ns
Cluster number	H	17.5	22.2 (27 %)	18.67 (–16 %)	13.1 a (–30 %)	17.1 (31 %)	18.7
	L	21.2	20.7 (–2 %)	24.25 (17 %)	20.7 b (–15 %)	19.0 (–8 %)	19.7
	PS	ns	ns	ns	***	ns	*
	Y						*
	PS × Y						*
Yield without rot	H	1.47	2.39 (63 %)	2.28 b (–5 %)	0.91 (–60 %)	1.69 (86 %)	1.76
	L	1.78	1.71 (–4 %)	1.56 a (–9 %)	1.12 (–28 %)	1.95 (74 %)	1.70
	PS	ns	ns	*	ns	ns	*
	Y						***
	PS × Y						**
Pruning weight	H	570.0	720.7 b (26 %)	424.3 (–41 %)	563.5 (33 %)	735.1 b (30 %)	681.6
	L	433.3	496.3 a (15 %)	533.8 (8 %)	747.8 (40 %)	530.2 a (–29 %)	495.8
	PS	ns	*	ns	ns	***	
	Y						ns
	PS × Y						
RI	H	4.13	3.6 (–13 %)	4.96 (38 %)	1.59 a (–68 %)	2.58 a (62 %)	3.17
	L	6.28	3.94 (–37 %)	4.44 (13 %)	2.91 b (–34 %)	4.39 b (51 %)	4.3
	PS	ns	ns	ns	**	***	
	Y						***
	PS × Y						ns

Statistical significance: *p < 0.01; **p < 0.005; ***p < 0.001.

incidence compared to L (0.72 kg). Regarding pruning weight, there was no consistent biomass production at the sites. In two seasons, 2020 and 2023, H plots had greater pruning weight than L (0.21 kg difference on average). Finally, vine balance (measured as RI) was statistically different in the last two seasons of the study (2022 and 2023), where L showed higher values compared to H (1.57 higher on average).

Table 4 shows the differences obtained in berry composition at harvest. Significant differences were found on average between plots in two variables only, for example, final sugar content (measured as °Brix) and total acidity; particularly in 2023, berries harvested in L had a sugar content of 0.9 °Brix higher than those harvested in H.

In terms of acidity, the 2020 and 2023 vintages exhibited greater differences between plots. Berries from H plots obtained higher acidity content than those from L plots (+0.98 g and +1.64 g in 2020 and 2023, respectively). Berry pH and total phenolic index showed no significant differences between years and plot locations.

3. Albariño responses to climate conditions

The Pearson correlation matrix made to elucidate the relationships between local climate and Albariño agronomic performance and oenological potential showed that berry composition variables were more affected by exposure to the Atlantic Ocean than yield components variables. Berry composition of Albariño showed significant differences in plots distinguishing between High or Low Atlantic Ocean exposition (Figure 2). Berries with higher sugar content (°Brix levels) and lower total acidity were associated with L plots experiencing greater thermal amplitude during the ripening period and higher January minimum temperature (r = 0.62; p=0.003; and r=0.83; p=0.0001, respectively) (Figure 2A,C). pH and berry weight resulted in significant differences between plots experiencing extreme temperatures as maximal

TABLE 4. Albariño berry primary and secondary composition at harvest during the 2019 to 2023 growing seasons comparing High (H) and Low (L) exposure to the Atlantic Ocean (Plot Site— PS), the year effect (Y) and the interaction between year and plot site (PS × Y). Values in brackets represent the variance percentage of the variable of the year compared to the previous one.

Variables	Sites	2019	2020	2021	2022	2023	Mean
°Brix	H	20.8 a	22.8 a (10 %)	19.6 a (–14 %)	19.3 a (–2 %)	21.0 a (9 %)	20.6
	L	21.4 a	23.1 a (8 %)	19.4 a (–16 %)	19.3 a (–1 %)	21.9 b (13 %)	21.0
	PS	ns	ns	ns	ns	***	*
	Y						***
	PS × Y						ns
Total Acidity (g H_2SO_4.l^{-1})	H	7.25 a	5.33 b (–26 %)	5.09 a (–5 %)	7.49 a (47 %)	8.04 b (7 %)	6.50
	L	5.12 a	4.35 a (–15 %)	5.29 a (22 %)	6.85 a (29 %)	6.40 a (–7 %)	5.40
	PS	ns	*	ns	ns	***	
	Y						*
	PS × Y						ns
pH	H	3.09 a	3.17 a (3 %)	3.05 a (–4 %)	3.09 a (1 %)	3.07 a (–1 %)	3.10
	L	3.19 a	3.16 a (–1 %)	3.01 a (-5 %)	3.05 a (1 %)	3.08 a (1 %)	3.10
	PS	ns	ns	ns	ns	ns	ns
	Y						ns
	PS × Y						ns
TPI	H	29.80 a	73.4 a (146 %)	29.7 a (–60 %)	41.38 a (39 %)	34.67 a (–16 %)	35.2
	L	30.15 a	47.7 a (58 %)	34.9 a (–27 %)	44.75 a (28 %)	43.17 a (–4 %)	40.0
	PS	ns	ns	ns	ns	ns	ns
	Y						*
	PS × Y						ns

Statistical significance: *$p < 0.01$; **$p < 0.005$; ***$p < 0.001$.

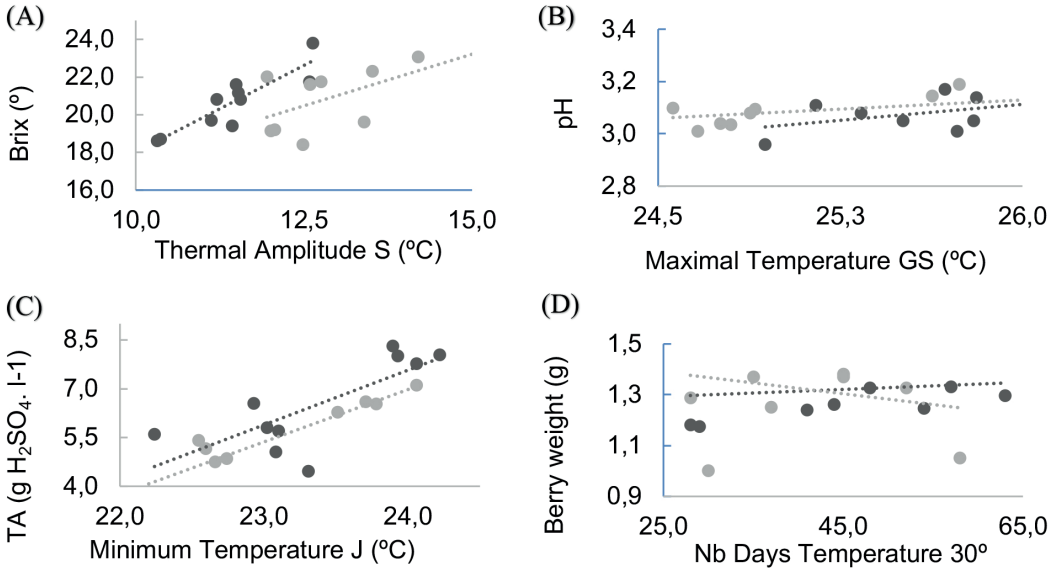


FIGURE 2. Plasticity assessment between Albariño plots at different exposures to the Atlantic Ocean (High – dark grey circle; and L – light grey circle). (A) °Brix at harvest and Thermal Amplitude during summer ($r = 0.62$; $p < 0.003$), (B) pH at harvest and maximum temperature in the Growing Season ($r = 0.75$; $p < 0.0001$), (C) Total Acidity at harvest and January minimum temperature ($r = 0.83$; $p < 0.0001$), (D) Berry weight at harvest and Number of days above 30°C ($r = –0.67$; $p < 0.01$).

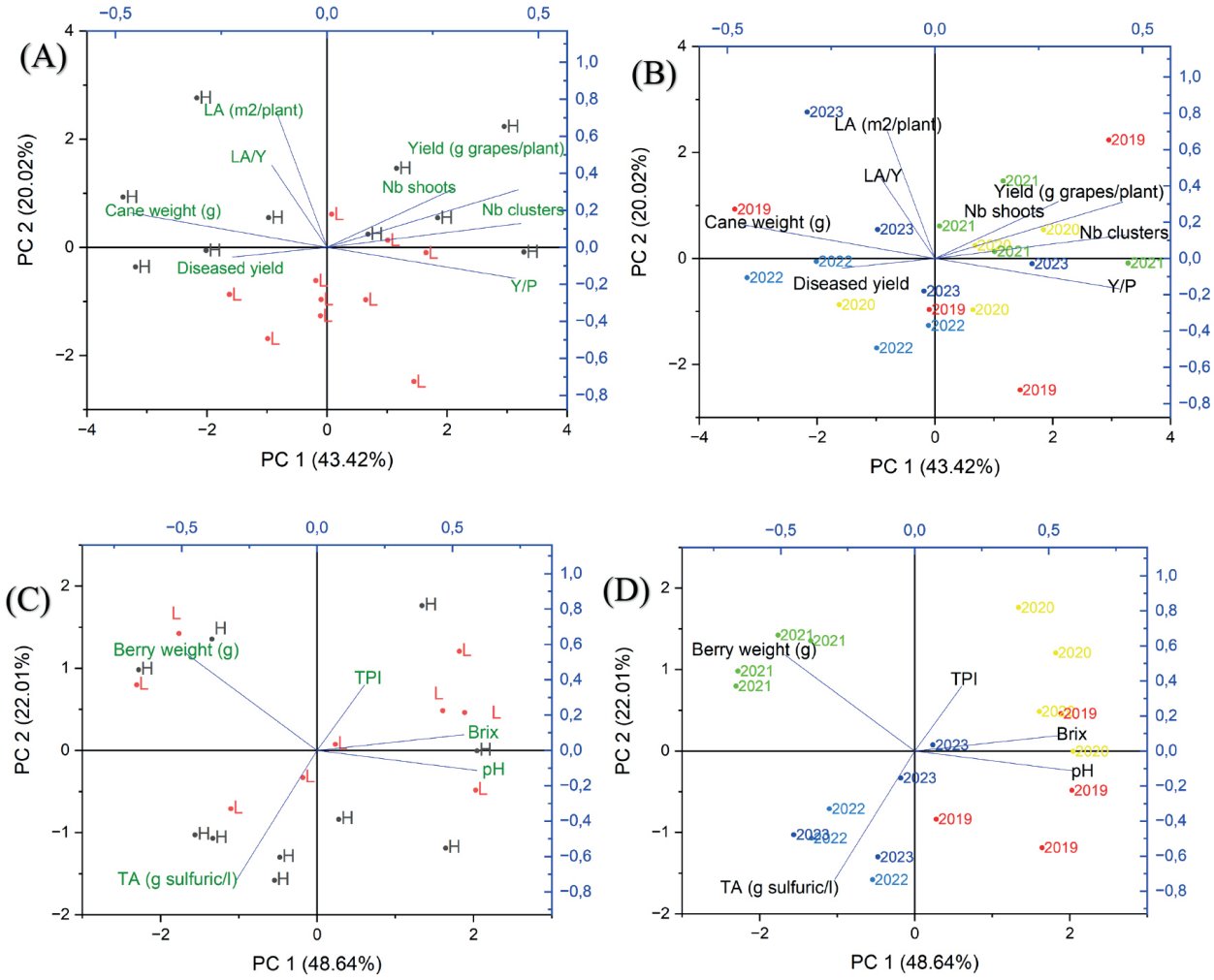


FIGURE 3. Principal Component Analysis. (A) Yield components variables and plot location at different exposures to the Atlantic Ocean (High as H and Low as L), (B) Yield components variables and year, (C) Berry composition variables and plot location, (D) Berry composition variables and year. For the four figures, the points represent each plot.

temperature during the growing season (Figure 2B) and number of days with temperatures above 30 ºC (Figure 2D) ($r = 0.75$; $p = 0.0001$; and $r = –0.67$; $p = 0.01$, respectively).

PCA analysis of Albariño performance comparing plots, location and years showed that berry composition variables were more significant than yield components (70.7 % and 63.4 % of the total variability, respectively) (Figure 3). In terms of yield components, PCA showed that H plots were separated from L plots and were highly associated with cane weight, yield, number of shoots per plant and number of clusters (Figure 3A). When the season was considered, there was no clear association with yield measurements, except for the 2022 vintage where yield was associated with the incidence of bunch rot (Figure 3B).

A clear discrimination between berry acidity and sugar content was determined between plots with different expositions to the Atlantic Ocean (Figure 3C), where higher °Brix were reached in L plots. Also, we found discrimination between final berry composition and season (Figure 3D), showing an interesting finding through the five studied years: 2020 was associated with the total polyphenol index, and 2022 and 2023 were associated with total acidity.

DISCUSSION

The discussion below focuses on the main results obtained in this study: i) spatial climate variability in the vineyards is higher when the season climate conditions are warm (H and L exposition to the Atlantic Ocean present higher differences in temperature), ii) Albariño demonstrates adaptability in a Uruguayan terroir, and iii) Albariño shows some plasticity in its final grape composition in response to varying local climates and different levels of exposure to the Atlantic Ocean, rather than agronomic variables.

1. Climate variability in the vineyards is greater under warmer seasonal conditions

Among the five growing seasons studied, 2019 and 2022 were classed as wet, with precipitation exceeding the average by 348 mm and 208 mm, respectively. For viticulture in Uruguay, having lower rainfall during ripening is desirable to mitigate the risk of disease. Despite the high water availability in 2019 and 2022, only 2022 experienced extreme precipitation during berry ripening (128 mm above average), resulting in Botrytis rot in Albariño. In the 32 years from 1991 to 2023, Fourment *et al.* (2024) observed no statistical trend in precipitation (increase or decrease) in eastern Uruguay. However, the decreasing trend in rainy days combined with an increasing trend in dry days, raises questions about the need to adapt grapevines to water deficit conditions, even in the presence of wet seasons. The last two seasons of the study, particularly the summer of 2023, were influenced by ENSO La Niña, leading to a severe drought compounded by a heat wave as experienced in other countries of central South America (Arias *et al.*, 2023). While the reduced amount of rainfall cannot be directly attributed to climate change, the higher regional temperatures can contribute to decreased water availability (Arias *et al.*, 2023). This suggests that climate change likely exacerbates agricultural drought by adding heat stress to water stress on crops (Arias *et al.*, 2023). Considering viticulture, such heat and water stress conditions can reduce berry yield, inhibit vine canopy development, and alter grapevine composition and typicity (Ferrer *et al.*, 2014; van Leeuwen and Destrac-Irvine, 2017), thereby impacting wine characteristics. This highlights the need for viticulturists, consultants, and oenologists in Uruguay to adapt to climate variability and extreme events to maintain vineyard productivity and sustainability, in which case, cultivar plasticity is crucial to a better adaptation to climate conditions.

Despite annual variability, the average precipitation during the studied years was sufficient to achieve vine water requirements (Williams, 2014), except in 2023, the driest season of the past 32 years (Tachini *et al.*, 2023b). The 2023 season, being the driest and hottest, exhibited the greatest differences between plot locations, indicating significant spatial variability.

The vineyards' exposure to the Atlantic Ocean resulted in differences in thermal indicators between plots with higher and lower exposure. The moderating Atlantic Ocean's influence is evident through various indices: heat accumulation (GDD), average temperatures during the growing season (TN, TX), specific phenological periods like flowering (TXNov and TNNov) and ripening (CNI, TXJan, TNJan), extreme temperatures (ND30 and ND35) and the thermal impact during potential development of sea breeze circulation (Freq.H-0.5 and Freq.H-1). For eastern Uruguay, the thermal amplitude is not a major mode of variability, unlike the southern wine region as demonstrated by Fourment *et al.* (2017). However, the CNI, TNNov and TNJan indicators displayed greater spatial variability, indicating that minimal temperature may be a crucial factor in distinguishing thermal conditions across this region over both space and time.

The sea breeze's influence on the spatial variability of temperature was significant in the region during the warm season of 2023, as shown in Table 2 in the frequency of the number of hours with a decrease in temperature at different intensities (0.5 ° and 1.0 °) at the time of maximum temperature (between 11:00 and 16:00 Local hour), corroborating results over the South Africa vineyards (Bonnardot *et al.*, 2005). Fourment *et al.* (2014) showed that during berry ripening, a vineyard ~30 km inland from La Plata River spent less time (44 hours) experiencing a temperature decrease in the afternoon linked to sea breeze development, compared to Garzón vineyards (53 hours for H plots and 35 for L plots). This indicates greater differences within the region than in two different coastal regions. Garzón vineyards experience an average of 113 hours of temperature drop with greater exposure to the Atlantic Ocean, compared to 72.3 hours with less exposure. Although differences in ocean exposure do not significantly differentiate plots, the high thermal impact is statistically differentiated during the hottest summer. The small topographic differences between plots do not affect local events like sea breezes, but H plots are more impacted

during dry seasons, showing greater temperature spatial variability. This finding is crucial for understanding climate change impacts, as vineyards exposed to sea breezes can experience reduced extreme temperatures during ripening, minimising thermal stress and preventing degradation of primary and secondary metabolites caused by high temperatures (Carey *et al.*, 2003; Sadras and Moran, 2012; Poni *et al.*, 2018).

However, considering mean temperature conditions over the season (as expressed by GDD), cooler conditions are experienced in L plots closer to the ocean. Thus, the drop in temperature associated with the arrival of the sea breeze inland could be minimised compared to the data recorded in H plots. During heat waves, evaluating the duration that grapevines remain below critical thermal thresholds (such as 30 °C or 35 °C) can improve the precision of our assessments, particularly when considering the cooling effect of sea breezes. This aspect presents a potential bias in our methodology for studying the influence of sea breezes in the coastal vineyards of the region. To address this, further investigation is needed, potentially incorporating regional atmospheric simulations similar to those previously conducted in the vineyards of Southwestern Cape Province, South Africa (Bonnardot *et al*., 2002; Bonnardot *et al*., 2005; Soltanzadeh *et al*., 2016).

Similarly, bioclimatic indices for viticulture in Uruguay should be further explored in relation to the ENSO phases, like the research conducted by Lemos Kaltbach *et al.* (2024) in Brazil. This approach will improve our understanding of the impacts of ENSO on Uruguayan viticulture and contribute to developing more resilient vineyard management practices.

2. Albariño shows adaptability in the Uruguayan Atlantic eastern terroir

To ensure sustainable production systems, a medium-term study of the adaptability of cultivars in consecutive growing seasons in each terroir is necessary. An analysis of five consecutive growing seasons of Albariño, a cultivar actively promoted in Uruguayan viticulture has demonstrated its potential due to its favourable agronomic and oenological performance in eastern Uruguay.

The Albariño cultivar in Eastern Uruguay has proven to be productive, averaging over 7 tons per hectare, and relatively stable over five seasons. Low temperatures during flowering (November in Uruguay) could impact fruit set and thus final yield in the season (Keller *et al.*, 2010) and cluster number of the next season (May, 1961). This was the case in the spring of 2021, with November minimum temperatures being 0.9 °C and 1.1 °C lower than the five-year average in the H and L plots, respectively. These cool spring conditions significantly affected the final yield, with further spatial differences: L plots produced 0.72 kg per plant less than H plots. The lower maximum temperatures during spring 2021 could explain the limited cluster number of the 2022 season for both plot locations, with an average difference of 7.6 clusters per vine between H and L plots. In terms of berry quality, amongst the wet summers of 2019, 2021 and 2022 (receiving 283, 218 and 319 mm of precipitation, respectively, over January and February), Albariño experienced yield losses caused by *Botrytis* rot incidence in 2022 only, showing some tolerance to bunch rot. This result has relevance to climate change scenarios, as increased precipitation is projected during summer and autumn (Intergovernmental Panel on Climate Change, 2023).

In terms of Albariño oenological potential for the five studied vintages, the average berry composition at harvest reached 202.7 g of sugars (20.8 °Brix) and 5.95 g H_2SO_4.l^{-1} of total acidity, which are ideal values for producing finely balanced wines. Sugar content exhibited significant statistical differences between years ($p < 0.001$). As the viticulture sector has started to prioritise sustainability by implementing national production programs and certifications for sustainable grape management practices (Instituto Nacional De Vitivinicultura, 2024), these findings are highly relevant. Albariño's consistent yield levels and high-quality berry parameters under temperate and sometimes humid conditions suggest that it is a variety well-situated for continued planting in Uruguay. In the context of climate change, the moderate temperatures of the Atlantic eastern terroir, combined with the production of a white cultivar that can express style and quality, represent two complementary adaptive strategies for mitigating climate change impacts, as proposed by Naulleau *et al.* (2021).

3. Albariño shows some plasticity in its final grape composition in response to varying local climates and different levels of exposure to the Atlantic Ocean, rather than agronomic variables under field conditions in Uruguay

Assessing cultivar plasticity under different plot climatic conditions can help viticulturists choose the best-suited cultivars to adapt to climate change and variability. This evaluation also helps improve disease tolerance, optimise vineyard management practices (such as pruning and harvest timing), and maintain berry and wine quality and typicity. Multivariate analysis of yield and berry composition data, considering plot exposure and seasonal climate, has revealed that: 1) yield components have a lower impact on vineyards exposure compared to the berry composition at harvest; 2) the correlations between berry composition and plot exposure are greater under warmer and drier conditions.

When yield components are analysed as a response to Albariño plasticity of local climate, our results show differences in yield (g/plant), number of clusters and cane weight of the vines from the plots of high exposure (Figure 3A), higher yield (0.8 kg higher on average) with lower clusters per vine (1 less cluster) and greater biomass (186 g more on average) (Table 3). However, the season effect is more complex because yield is not only driven by factors in the current season (May, 1961), and the previous season temperature could affect yield components, as discussed above.

Albariño berry composition at harvest shows sensitivity to ocean exposure in two primary metabolites (sugar and acidity) which is amplified between plots under drier and warmer conditions such as 2023. These results are not in agreement with Wu *et al.* (2019), who argue that moderate temperature increases did not impact primary metabolites in Sauvignon blanc. A demonstration of Albariño plasticity is shown in Figure 2A,C, where the relationship between different temperature variables and berry composition at harvest is evident. Vineyards with lower ocean exposure exhibit higher sugar content in berries, a trait that is highly correlated with the thermal difference between day and night during ripening. This increased thermal amplitude, as analysed by Kliewer (1973), acts as a precursor for higher sugar content in berries due to more photosynthetic activity.

Conversely, Albariño vineyards with higher ocean exposure led to greater total acidity (TA) in berries, due to less extreme temperatures. Malic and tartaric acid are the two main organic acids in grape berries. Only malic acid is metabolised by the ripening berry, and thus, its content is impacted by temperature (Rienth *et al.*, 2021). The correlation between TA and minimum temperature in January highlights the impact of plot location on berry composition. While Wu *et al.* (2019) suggested that moderate temperature increases do not significantly influence sugar and acid metabolism in Sauvignon blanc cv., our findings indicate that meso-climate differences do affect these compounds in Albariño. As reported by Sweetman *et al.* (2014), the degradation of malic acid concentration is accelerated by high temperatures, and it depends on thermal amplitude.

Other variables, such as pH and berry weight, do not demonstrate clear plasticity to local climate conditions. The relative stability of pH across different seasons and sites emphasises its role in determining the optimal harvest time, which explains its consistent levels despite varying climatic conditions.

Fourment *et al.* (2017) reported similar results for the red cultivar Tannat in southern Uruguay, highlighting the influence of temperature spatial variability on secondary metabolite production. The same results were found in the Atlantic eastern region for the same red cultivar in Tachini *et al.* (2023a). One limitation of our present study is that we only measured the total phenolic index as a secondary compound. It would be beneficial to explore the impact of different temperature thresholds on aroma and aroma precursors in grapes, as suggested by Wu *et al.* (2019) and Carey *et al.* (2003). The variability observed in only two contrasting local climate conditions (H and L) needs to be further investigated. For instance, the indirect method of analysing two contrasting environments can be considered a localised phenomenon, as discussed by Bonada and Sadras (2014). However, the observed contrasts across growing seasons, due to interannual variability and differing levels of Atlantic Ocean exposure across locations, improve our understanding of this economically important variety for both the country and the region.

CONCLUSIONS

This study focused on seasonal and spatial temperature variability over a limited 5-year period (2019–2023) in field conditions of Albariño vineyards in an emerging wine region in eastern Uruguay by assessing the impacts on the grapevine cultivar in terms of grape yield and berry composition.

The seasonal temperature variability in eastern Uruguay was highly influenced by precipitation patterns linked to the large-scale ENSO, while spatial temperature variability was significantly influenced by the local factor of the proximity of the Atlantic Ocean. High-exposure vineyards experienced the cooling influence of the sea breeze more frequently, reducing thermal stress during critical phenological periods. The study of thermal indicators, such as mean night temperatures and extremely high-temperature events, revealed important spatial variability, highlighting the importance of local maritime influences and topographic factors in shaping the region's thermal landscape.

Future studies will focus on examining the variability of bioclimatic indices for viticulture in relation to ENSO phases, aiming to deepen our understanding of ENSO's impacts on Uruguayan viticulture. Additionally, sea breeze simulations using a regional atmospheric model will be conducted to improve the study of local maritime air circulation's climatic effects on vineyards.

The temperature differences within the vineyards affected grape composition more than yield, showing how adaptable this white cultivar is to changing climates. Albariño's response to ocean exposure is demonstrated in its sugar and acidity, with the biggest differences seen during the very hot and dry conditions of 2023. By taking advantage of local climatic factors, like the cooling effect of the Atlantic Ocean, viticulturists can make better decisions on managing their vineyards to reduce the impacts of climate change. This adaptive approach is essential for keeping viticulture sustainable in eastern Uruguay and highlights the importance of choosing the right grape cultivar and understanding the local climate to ensure future vineyard success. Further studies on the impact of temperature and precipitation spatial and temporal variability on secondary metabolites of grapes and wine are essential to propose specific adaptative management practices and to identify wine styles. A longer series of data and an enlarged trial of measurement are needed to consolidate these results. This is why the monitoring of cultivars, and the maintenance and development of a network of thermal sensors and weather stations are of utmost importance for such interdisciplinary studies that require field observations and measurements over long periods.

ACKNOWLEDGEMENTS

This work was supported by the CSIC VUSP Project, Bodega Garzón by Asistencia Técnica, and the ANII VCT Project (MOV_CA_2023_1_176628). We thank Germán Bruzzone and Manuel Macchiavello from Bodega Garzón for giving us access to their vineyards for this study. We especially thank Lucila Bentancor for her help in field measurements and laboratory analysis.

REFERENCES

Anderson, W., Seager, R., Baethgen, W., Cane, M. (2017). Crop production variability in North and South America forced by life-cycles of the El Niño Southern Oscillation. *Agricultural and Forest Meteorology*, 239, 151-165. https://doi.org/10.1016/j.agrformet.2017.03.008

Arias, P., Rivera, J. A., Sörensson, A. A., Zachariah, M., Barnes, C., Sjoukje, P., Kew, S., Vautard, R., Koren, G., Pinto, I., Vahlberg, M., Singh, R., Raju, E., Li, S., Yang, W., Vecchi, G. A., Otto, F. E. L. (2023). Vulnerability and high temperatures exacerbate impacts of ongoing drought in Central South America. World and weather attribution organisation. WWA-Argentina y Uruguay drought scientific report. Available in: https://bit.ly/42fGDpS.

Barreiro, M. (2009). Influence of ENSO and the South Atlantic Ocean on climate predictability over Southeastern South America. *Climate Dynamics*, 53, 1493-1508. https://doi.org/10.1007/s00382-009-0666-9

Blanco-Ward, D., Queijeiro, J. M. G., Jones, G. V. (2007). Spatial climate variability and viticulture in the Miño River Valley of Spain. *Vitis.* 46, 63–70. https://doi.org/10.5073/vitis.2007.46.63-70

Bonada, M., Sadras V. O. (2014). Review: critical appraisal of methods to investigate the effect of temperature on grapevine berry composition. *Australian Journal of Grape and Wine Research*, 21, 1-17. https://doi.org/10.1111/ajgw.12102

Bonnardot, V., Planchon, O., Carey, V.A., Cautenet S. (2002). Diurnal wind, relative humidity and temperature variation in the Stellenbosch-Groot Drakenstein winegrowing area. *South African Journal of Enology and Viticulture*, 23, 62-7. https://doi.org/10.21548/23-2-2156

Bonnardot, V., Planchon, O., Cautenet, S. (2005). The sea breeze development under an offshore synoptic wind in the South Western Cape and implications for the Stellenbosch wine producing area. *Theoretical and Applied Climatology*, 81, 203-218. https://doi.org/10.1007/s00704-004-0087-y

Bonnefoy, C., Quénol, H., Bonnardot, V., Barbeau, G., Madelin, M., Planchon, O., Neethling, E. (2013). Temporal and spatial analysis of Temperatures in a French wine-producing area: the Loire Valley. *International Journal of Climatology*, 33, 1849-1862. https://doi.org/10.1002/joc.3552

Carbonneau, A., Moueix, A., Leclair, N., Renoux, J. (1991). Proposition d'une méthode de prélèvement de raisin à partir de l'analyse de l'hétérogénéité de maturation sur un cep. *Bulletin OIV*, 64, 679-690.

Carey, V. A., Bonnardot, V., Schmidt, A. Theron J. C. D. (2003). The interaction between vintage, vineyard site (mesoclimate) and wine aroma of *Vitis vinifera* L. cvs. Sauvignon blanc, Chardonnay and Cabernet Sauvignon in the Stellenbosch-Klein Drakenstein wine producing area. *Bulletin OIV*, 76, 4-29.

De Mello, S, Renom, M. (2024). *Caracterización de las olas de calor en Uruguay, análisis de la variabilidad interanual y variabilidad diaria*. Master Degree Rapport. Programa de Ciencias Básicas Geociencias. Universidad de la República. Montevideo, Uruguay. 163 p.

de Rességuier, L., Mary, S., Le Roux, R., Petitjean, P., Quénol, H., van Leeuwen, C. (2020). Temperature variability at local scale in the Bordeaux area. Relations with environmental factors and impact on vine phenology. *Frontiers in Plant Science*, 11. https://doi.org/10.3389/fpls.2020.00515

Falcao, L. D., Burin, V. M., Sidinei Chaves, E., Vieira, H. J., Brighenti, E., Rosier, J.-P., Bordignon-Luiz, M. T. (2010). Vineyard altitude and mesoclimate influences on the phenology and maturation of Cabernet-Sauvignon grapes from Santa Catarina State. *OENO One*, 44, 135. https://doi.org/10.20870/oeno-one.2010.44.3.1470

Ferrer, M., Pedocchi, R., Michelazzo, M., González-Neves, G., Carbonneau, A. (2007). Delimitación y descripción de regiones vitícolas del Uruguay en base al método de clasificación climática multicriterio utilizando índices bioclimáticos adaptados a las condiciones del cultivo. *Agrociencia Uruguay*, 11, 47-56. https://doi.org/10.31285/AGRO.11.768

Ferrer, M., Echeverría, G., Carbonneau, A. (2014). Effect of berry weight and its components on the contents of sugars and anthocyanins of three varieties of *Vitis vinifera* L. under Different water supply conditions. *South African Journal of Enology and Viticulture*, *35*, 103-113.

Ferrer, M., Pereyra, G., Salvarrey, J., Arrillaga, L., Fourment, M. (2020). ' Tannat ' (*Vitis vinifera* L.) as a model of responses to climate variability. *Vitis*, 59, 41-46. https://doi.org/10.5073/vitis.2020.59.41-46

Ferretti, C. (2021). Topoclimate and wine quality: Results of research on the Gewürztraminer grape variety in South Tyrol, northern Italy. *OENO One*, 55, 313-335. https://doi.org/10.20870/oeno-one.2021.55.1.4531

Fourment, M., Ferrer, M., Quénol H. (2013). *Vitis vinifera* L. cv. Tannat: respuesta a la variabilidad climática. *Agrociencia Uruguay,* 17, 33-44. https://doi.org/10.31285/AGRO.17.433

Fourment, M., Bonnardot, V., Planchon, O., Ferrer, M., Quénol, H. (2014). Circulation atmosphérique locale et impacts thermiques dans un vignoble côtier : observations dans le sud de l'Uruguay. *Climatologie*, 11, 47-64. https://doi.org/10.4267/climatologie.589

Fourment, M., Ferrer, M., González-Neves, G., Barbeau, G., Bonnardot, V., Quénol, H. (2017). Tannat grape composition responses to spatial variability of temperature in a coastal wine region. *International Journal of Biometeorology*, 61, 1617–1628. https://doi.org/10.1007/s00484-017-1340-2

Fourment, M., Ferrer, M., Barbeau, G., Quénol H. (2020). Local perceptions, vulnerability and adaptive responses to climate variability in a winegrowing region in Uruguay. *Environmental Management*, 66, 590-599. https://doi.org/10.1007/s00267-020-01330-4

Fourment, M., and Piccardo, D. (2023). "What grapes and wines to expect with the drought?". *Agrociencia Uruguay*, 27, 1-5. https://doi.org/10.31285/AGRO.27.1206

Fourment, M., Tachini, R., Ferrer, M. (2024). Adaptation to climate change and variability of viticulturists in Uruguay (Chapter 9). In: *Latin American Viticulture Adaptation to Climate Change*. *Perspectives and Challenges of Viticulture Facing up Global Warming*. Ed.: Gutierrez-Gamboa G., Fourment M. Springer Nature, 75-85. https://doi.org/10.1007/978-3-031-51325-1_9

Gavrilescu, C., Bois, B. (2016). Chardonnay wines climate plasticity: A worldwide geographical approach / Plasticité des vins issus de cépage Chardonnay au climat : une aproche géographique à l'échelle planétaire. *BIO Web of conferences*, 7, 01013. https://doi.org/0.1051/bioconf/20160701013

González-Neves, G., Ferrer, M., Gil, G., Charamelo, D., Balado, J., Barreiro, L., Bochicchio, R., Gatto, G., Tessore, A. (2010). Estudio plurianual del potencial polifenólico de uvas Tannat en el sur de Uruguay. *Agrociencia Uruguay*, 14(2), 10-21. https://doi.org/10.2477/vol14iss2pp10-21

Gladstone, J. (2015). Viticulture and environment. Second edition. Trivinum Press. Tanunda, Australia, 320p.

Glories, Y., Augustin, M. (1993). Maturité phénolique du raisin, conséquences technologiques: application aux millésimes 1991 et 1992. Compte Rendu Colloque Journée Techn. CIVB, Bordeaux. p. 56-61.

Hall, A., Jones, G. V. (2010). Spatial analysis of climate in winegrape-growing regions in Australia: Climate in winegrape growing regions in Australia. *Australian Journal of Grape and Wine Research*, 16, 389–404. https://doi.org/10.1111/j.1755-0238.2010.00100.x

Hareau, A., Hofstadter, R., Saizar, A. (1999). Vulnerability to climate change in Uruguay: potential impacts on the agricultural and coastal resource sectors and response capabilities. *Climate Research,* 12, 185–193. https://doi.org/10.3354/cr012185

Instituto Nacional de Vitivinicultura (2024). I.NA.VI. *Estadísticas De Viñedos 2023, Datos Departamentales*. Available in: https://www.inavi.com.uy/vinedos/estadisticas/

Intergovernmental Panel on Climate Change (2023). I.P.C.C. Point of Departure and Key Concepts. In: *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press; 2023:121-196.. https://doi.org/10.1017/9781009325844.003

Jones, G. V. (2006). "Climate and terroir: impacts of climate variability and change on wine" in Fine Wine and Terroir-the Geoscience Perspective. Macqueen, R. W. and Meinert, L. D. (Editors), Geoscience Canada Reprint Series Number 9, Geological Association of Canada, St. John's, Newfoundland, 247 pages.

Keller, M. J., Tarara, J. M., Mills, L. J. (2010). Spring temperatures alter reproductive development in grapevines. *Australian Journal of Grape and Wine Research*, 16, 445-454. https://doi.org/10.1111/j.1755-0238.2010.00105.x

Kliewer, W. M. (1973). Berry composition of *Vitis vinifera* cultivars as influenced by photo- and nycto- temperatures during maturation. *American Society of Horticultural Sci*ence, 98, 153–159. https://doi.org/10.21273/JASHS.98.2.153

Lemos Kaltbach, P., Kaltbach, S., Domingues, F., Herter, F., & Costa, V. (2022). Relationship between the El Niño-Southern Oscillation and yield and sugar content of wine grapes grown in Santana do Livramento, RS, Brazil. *Ciência Agrária*, 43, 2031-2044. https://doi.org/10.5433/1679-0359.2022v43n5p2031

Lemos Kaltbach, P., Kaltbach, S., Costa, V., Domingues, F., & Herter, F. (2024). Viticultural climate variability at Santana do Livramento, Campanha Gaúcha, Brazil: associations with the El Niño-Southern Oscillation. *Revista Thema*. 23, 545-557. https://doi.org/10.15536/thema.V23.2024.545-557.3770

Liu, J., Zhang, L., Xu, X., Niu, H. (2016). Understanding the wide geographic range of a clonal perennial grass: plasticity versus local adaptation. *AoB PLANTS,* 8, plv141. https://doi.org/10.1093/aobpla/plv141

Madelin, M., Bois, B., & Quénol, H. (2014). "Variabilité topoclimatique et phénologique des terroirs de la montagne de Corton (Bourgogne)," in *Changement Climatique et Terroirs Viticoles*, Quénol H. (Editor), Lavoisier Tec&doc, Paris, 215–227.

May, P. (1961). The value of an estimate of fruiting potential in the Sultana. *Vitis*, 3, 15-26. https://doi.org/10.5073/vitis.1961.3.15-26

Naulleau, A., Gary, C., Prévot, L., Hossard, L. (2021). Evaluating Strategies for Adaptation to Climate Change in Grapevine Production–A Systematic Review. *Frontiers in Plant Science*, 11, 607859. https://doi.org/10.3389/fpls.2020.607859

PlantGrape (2024). Albariño wine grape variety description. Available in: https://www.plantgrape.fr/en/varieties/fruit-varieties/300

Penalba, O. C., Rivera, J. A. (2016). Precipitation response to El Niño / La Niña events in Southern South America – emphasis in regional drought occurrences. *Advances in Geoscience*, 42, 1–14. https://doi.org/10.5194/adgeo-42-1-2016

Pieri, P., de Rességuier, L., Ollat, N., Renaud, C., Thibon, C., Cholet, C., Lecouriex, D., Guillaumie, S., Hilbert, G. (2022). Spatial variability of temperature is linked to grape composition variability in the Saint-Emilion winegrowing area. IVES Conference Series, Terclim 2022.

Poni, S., Gatti, M., Palliotti, A., Dai, Z., Duchêne, E:, Truong, T. T., Ferrara, G., Mataresse, A. S. M., Gallotta, A., Bellincontro, A., Mencarelli, F., Tombesi, S. (2018). Grapevine quality: a multiple choice issue. *Scientia Horticulturae,* 234, 445–462. https://doi.org/10.1016/j.scienta.2017.12.035

Ramos, M. C., Jones, G. V., Yuste, J. (2015). Spatial and temporal variability of cv. Tempranillo phenology and grape quality within the Ribera del Duero DO (Spain) and relationships with climate. *International Journal of Biometeorology*, 59, 1849–1860. https://doi.org/10.1007/s00484-015-0992-z

Ramos, M. C., Martínez de Toda, F. (2021). Interannual and spatial variability of grape composition in the Rioja DOCa show better resilience of cv. Graciano than cv. Tempranillo under a warming scenario. *OENO One*, 55, 85–100. https://doi.org/10.20870/oeno-one.2021.55.3.4695

Ravaz, M. (1911). L'effeuellage de la vigne. Annales d L'Ecole Nationale d'agriculture de Montpellier, 11, 216–244.

Rienth, M., Lamy, F., Schoenenberger, P., Noll, D., Lorenzini, F., Viret, O., Zufferey, V. (2020). A vine physiology-based terroir study in the AOC-Lavaux region in Switzerland. *OENO One*, 54, 699–716. https://doi.org/10.20870/oeno-one.2020.54.4.3756

Rienth, M., Vigneron, N., Darriet, P., Sweetman, C., Burbidge, C., Bonghi, C., Walker, R. P., Famiani, F., Castellarin, S. D. (2021). Grape Berry Secondary Metabolites and Their Modulation by Abiotic Factors in a Climate Change Scenario–A Review. *Frontiers in Plant Science*, 12, 643258. https://doi.org/10.3389/fpls.2021.643258

Rogiers, S. Y., Greer, D. H., Liu, Y., Baby, T., Xiao, Z. (2022). Impact of climate change on grape berry ripening: An assessment of adaptation strategies for the Australian vineyard. *Frontiers in Plant Science,* 13, 1094633. https://doi.org/10.3389/fpls.2022.1094633

Ruml, M., Korac, N., Vujadinovic, M., Vukovic, A., Ivaniševic, D. (2016). Response of grapevine phenology to recent temperature change and variability in the wine-producing area of Sremski Karlovci, Serbia. *Journal of Agricultural Science,* 154, 186–206. https://doi.org/10.1017/S0021859615000453

Rusticucci, M., Renom, M. (2008). Variability and trends in indices of quality-controlled daily temperature extremes in Uruguay. *International Journal of Climatology,* 28, 1083–1095. https://doi.org/10.1002/joc.1607

Sadras, V. O., Moran, M. A. (2012). Elevated temperature decouples anthocyanins and sugar in berries of Shiraz and Cabernet Franc. *Australian Journal of Grape and Wine Research,* 18, 115–122. https://doi.org/10.1111/j.1755-0238.2012.00180.x

Sadras, V. O., Reynolds, M. P., de la Vega, A. J., Petrie, P. R., Robinson, P. (2009). Phenotypic plasticity of yield and phenology in wheat, sunflower and grapevine. *Field Crop Research*, 110, 242-250. https://doi.org/10.1016/j.fcr.2008.09.004

Schlichting, C. D. (1986). Phenotypic plasticity in plants. *Plant Species Biology*, 17, 2-3, 85–88, 2002.

Soltanzadeh, I., Bonnardot V., Sturman A., Quénol H., Zawar-Reza P. (2016). Assessment of the ARW-WRF model over complex terrain: the case of the Stellenbosch Wine of Origin district of South Africa. *Theoretical and Applied Climatology*, 129, 1407-1427. https://doi.org/10.1007/s00704-016-1857-z

Sweetman, C., Sadras, V. O., Hancock, R. D., Soole, K. L., Ford, C. M. (2014). Metabolic effects of elevated temperature on organic acid degradation in ripening *Vitis vinifera* fruit. *Journal of Experimental Botany*, 65(20), 5975–5988. https://doi.org/10.1093/jxb/eru343

Tachini, R., Bonnardot, V., Ferrer, M., Fourment, M. (2023a). Topography interactions with the Atlantic Ocean and its impact on *Vitis vinifera* L. 'Tannat'. *Vitis*, 62, 163-177. https://doi.org/10.5073/vitis.2023.62.163-177

Tachini, R., Fourment, M. and Ferrer, M. (2023b). Precipitation variability in a temperate coastal region and its impacts on Tannat and Albariño cultivars. *Bio Web of Conference*. 44th World Congress of Vine and Wine, 68, 01006. https://doi.org/10.1051/bioconf/20236801006

Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology*, 124, 81-97. http://dx.doi.org/10.1016/j.agrformet.2003.06.001

Williams, L. E. (2014). Determination of evapotranspiration and crop coefficients for a Chardonnay vineyard located in a cool climate. *American Journal of Enology and Viticulture,* 65, 159-169. https://doi.org/10.5344/ajev.2014.12104

van Leeuwen, C., Destrac-Irvine, A. (2017). Modified grape composition under climate change conditions requires adaptations in the vineyard. *OENO One,* 51, 147–154. https://doi.org/10.20870/oeno-one.2017.51.2.1647

Verdugo-Vazquez, N., Orrego, R., Gutierrez-Gamboa, G., Reyes, M., Zurita-Silva, A., Balbontín, C., Gaete, N., Salazar-Parra, C. (2023). Climate trends and variability in the Chilean viticultural production zones during 1985–2015. *OENO One,* 57, 345–362. https://doi.org/10.20870/oeno-one.2023.57.1.7151

Vršič, S., Šuštar, V., Pulko, B., & Šumenjak, T. (2014). Trends in climate parameters affecting winegrape ripening in northeastern Slovenia. *Climate Research*, 58, 257–266. https://doi.org/10.3354/cr01197

Winkler, A. J. (1974). General Viticulture. Berkeley, CA: University of California Press. 710 pages.

Wu, J., Drappier, J., Hilbert, G., Guillaumie, S., Dai, Z., Geny, L., Delrot, S., Darriet, P., Thibon, C., Pieri, P. (2019). The effects of a moderate grape temperature increase on berry secondary metabolites. *OENO One*, 53. https://doi.org/10.20870/oeno-one.2019.53.2.2434

Young, P. R., Eyeghe-Bickong, H. A., du Plessis, K., Alexandersson, E., Jacobson, D. A., Coetzee, Z., Deloire, A., Vivier, M. A. (2016). Grapevine Plasticity in Response to an Altered Microclimate: Sauvignon Blanc Modulates Specific Metabolites in Response to Increased Berry Exposure. *Plant Physiology*, 170, 1235-1254. https://doi.org/10.1104/pp.15.01775

Yzarra, W., Sanabria, J., Cáceres, H., Solis, O., & Lhomme, J. P. (2015). Impact of climate change on some grapevine varieties grown in Peru for Pisco production. *OENO One*, 49, 103–112. https://doi.org/10.20870/oeno-one.2015.49.2.90