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CIÊNCIAS AGRÁRIAS

Viticultural climate variability at Santana do Livramento, Campanha Gaúcha, Brazil: associations with the El Niño-Southern Oscillation

***Variabilidade do clima vitícola em Santana do Livramento, Campanha Gaúcha, Brasil**: associações com o El Niño-Oscilação Sul*

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ABSTRACT

Meteorological conditions are fundamental factors in the development of viticulture anywhere in the world. Considering this, the viticultural climate and climate variability of Santana do Livramento, Campanha Gaúcha, Brazil, was characterized based on the three bioclimatic indices defined by the Geoviticulture Multicriteria Climatic Classification (MCC) System – cool night index (CI), heliothermal index (HI) and dryness index (DI) – as well as a modified dryness index ($DI_{modified}$). The observed climate variability was correlated with the three phases of the El Niño-Southern Oscillation (ENSO) – namely, El Niño, La Niña and neutral phase. El Niño events presented typically higher DI and $DI_{modified}$ values and lower HI values. La Niña events showed typically the opposite pattern, lower DI and $DI_{modified}$ values and higher HI values. Neutral conditions were characterized mostly by intermediate values for DI and $DI_{modified}$ as well as HI but the highest amplitude of CI values. The $DI_{modified}$ followed by DI and HI were the indexes presenting the highest correlation with the polarization of ENSO phases.

Keywords: La Niña; Campanha Gaúcha; *Vitis vinifera*; Bioclimatic indexes; Geoviticulture multicriteria climatic classification system.

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RESUMO

As condições meteorológicas são fatores fundamentais para o desenvolvimento da vitivinicultura em qualquer local do globo. Assim, caracterizou-se o clima vitícola de Santana do Livramento, Campanha Gaúcha, Brasil e sua variabilidade a partir dos três índices climáticos vitícolas preconizados pela metodologia do Sistema de Classificação Climática Multicritérios (CCM) Geovitícola - o índice de frio noturno (IF), o índice heliotérmico (IH) e o índice de seca (IS) -, além de um índice de seca flexibilizado ($IS_{flexibilizado}$). Correlacionou-se a variabilidade climática observada com as três fases do fenômeno El Niño-Oscilação Sul (ENOS) - El Niño, La Niña e fase neutra. Eventos de El Niño apresentaram tipicamente altos valores de IS e $IS_{flexibilizado}$ e baixos valores de IH. Eventos de La Niña apresentaram tipicamente o padrão inverso, menores valores de IS ou $IS_{flexibilizado}$ e altos valores de IH. Anos neutros apresentam tipicamente valores intermediários de IS ou $IS_{flexibilizado}$ e IH, e a maior amplitude de valores de IF. O $IS_{flexibilizado}$, seguido pelo IS e o IH foram as variáveis mais bem correlacionadas com a polarização das fases do ENOS.

Palavras-chave: *La Niña; Campanha Gaúcha; Vitis vinifera; Índices Bioclimáticos; Sistema de classificação climática multicritérios geovitícola.*

1. INTRODUCTION

Meteorological conditions are crucial for grape (*Vitis vinifera* L.) and wine production. These abiotic factors largely define the diversity of wine grape varieties which can be cultivated and the quality and typicity of wines produced in each region around the globe (Tonietto; Carbonneau, 2004).

The Geoviticulture Multicriteria Climatic Classification (MCC) System was developed specifically for vitiviniculture. It allows a broad characterization of climate and its variability in any location as well as comparisons between regions and vintages globally. This system employs three indexes: cool night index (CI); heliothermal index (HI); and dryness index (DI). The ranges of these indexes are divided into class intervals (Tonietto; Carbonneau, 2004).

The El Niño-Southern Oscillation (ENSO) is a source of climate variability at global level. This phenomenon is partially characterized by oscillations of temperature in the surface waters of the Pacific Ocean and is divided into three phases: warm (El Niño), cold (La Niña) and neutral (Timmermann *et al*., 2018). In South America, the ENSO is closely related to anomalies in weather and crops (Anderson *et al*., 2017). At Campanha Gaúcha, the ENSO alters rainfall, temperatures and relative humidity, causing quantitative and qualitative shifts in grapevine vintages (Kaltbach *et al*., 2022, 2023).

The objective of this work was to characterize the region under study – Santana do Livramento - regarding its viticultural climate and its viticultural climate variability, correlating the latter with the three phases of the El Niño-Southern Oscillation.

2. DEVELOPMENT

2.1. MATERIAL AND METHODS

The definition of ENSO events followed the records and criteria established by the National Oceanic and Atmospheric Administration (NOAA, 2023). The annual classification of the viticultural climate employed the three indexes defined by the MCC System: cool night index (CI), to express night or minimum temperatures during the grape maturation period; heliothermal index (HI), to express the availability of thermal energy above a threshold of 10°C, which correlates with plant phenology and the potential sugar accumulation in the berries; and dryness index (DI), to express the hydric conditions, by considering a water balance between precipitation and evapotranspiration (vineyard and soil), invariably starting in a soil containing 200mm of water storage, the same level set as maximum threshold of soil water storage capacity along the six months of the growing season. The indexes were calculated following the classical methodology of the MCC system for the Southern Hemisphere, applying calculations for the: one-month period from 1 March to 31 March, for CI; and the six-month period from 1 October to 31 March for both HI and DI (Tonietto; Carbonneau, 2004). Additionally, a modified dryness index ($DI_{modified}$) was calculated exactly as the DI but without considering any maximum threshold of soil water storage capacity along the growing season, in order to better estimate the water surplus in humid years (Alves; Tonietto, 2018). The ranges of these indexes are divided into class intervals shown in Table 1 (Tonietto; Carbonneau, 2004).

Table 1 – Classes of viticultural climate for the dryness index, heliothermal index and cool night index.

Index	Class of viticultural climate	Acronym	Class interval
Dryness index (DI, mm)	Humid	DI-2	150 < DI
	Subhumid	DI-1	50 < DI ≤ 150
	Moderately dry	DI+1	-100 < DI ≤ 50
	Very dry	DI+2	DI ≤ -100
Heliothermal index (HI)	Very cool	HI-3	HI ≤ 1500
	Cool	HI-2	1500 < HI ≤ 1800
	Temperate	HI-1	1800 < HI ≤ 2100
	Temperate warm	HI+1	2100 < HI ≤ 2400
	Warm	HI+2	2400 < HI ≤ 3000
	Very warm	HI+3	3000 < HI
Cool night index (CI, °C)	Warm nights	CI-2	18 < CI
	Temperate nights	CI-1	14 < CI ≤ 18
	Cool nights	CI+1	12 < CI ≤ 14
	Very cool nights	CI+2	CI ≤ 12

Source: adapted from the literature (Tonietto; Carbonneau, 2004).

The meteorological data included two different datasets derived from two different meteorological stations. Using data from two meteorological stations was necessary in order to cover a longer period for improving significance and reliability. They comprised rainfall, temperature and relative humidity data. The dataset referred as ‘Palomas’ or ‘Pa’, gently donated by a private company, was obtained in a meteorological station located inside vineyards at Palomas district, Santana do Livramento, Rio Grande do Sul state, Brazil (30°47’26’’S, 55°22’29’’O, 200m of altitude) and covered the period between January 1993 and August 2009. The other dataset referred as ‘Rivera’ or ‘Ri’, gently provided by the Instituto Uruguayo de Meteorologia (INUMET), was obtained from a neighboring meteorological station located within the city of Rivera, Uruguay (30º53'48’’S, 55º32'36’’O, 241m of altitude) and covered the period between January 2000 and April 2021.

The values obtained for the indexes and their respective class intervals were correlated with the occurrence of ENSO events. The correlations were investigated by frequency analysis and principal component analysis (PCA).

The codification for the production cycles employed the last two digits corresponding to the year of the vintage. For example, the production cycle ‘2001/2002’ is coded by ‘02’.

2.2. RESULTS AND DISCUSSION

The mean values obtained for the indexes within each of the two whole time series were close, resulting in the classification of the region into the same classes at Palomas and Rivera, respectively: CI – 17,00 e 17,18°C (CI-1, temperate nights); HI - 2751 e 2747 (HI+2, warm); DI – 183 e 192mm (DI-2, humid); and $DI_{modified}$ – 236 e 261mm.

The mean HI values observed denote that the region provides thermic conditions for completing and exceeding the whole phenological cycle of any *Vitis vinifera* L. cultivar. It means that, *a priori*, any cultivar can complete its maturation but they might be also subject to a certain risk of heat stress. The mean CI values (calculated for March, as preconized by the MCC System) denote that the early cultivars (harvested in early January, for example) tend to eventually face more challenging conditions for color and aroma development, while late cultivars (harvested in late February or March, for example) might benefit from cooler nights (Tonietto; Carbonneau, 2004).

The predominant high humidity, expressed by the mean DI values fitting within the DI class DI-2 (humid), is the most challenging factor for local grape growers. Overcast and rainy conditions during spring and early summer limit the availability of photoassimilates and increase the incidence of fungal diseases and the loss of injured berries. These factors compromise the adequate flowering and fruitset and, consequently, productivity (Kaltbach *et al.*, 2022, 2023; Keller, 2020; Vasconcelos *et al.*, 2009). The water surplus in the vineyard retards maturation and alters considerably the composition of grapes, while the moderate water deficit does not impair grape maturation (Keller, 2020).

Table 2 – Classification of the production cycles according to the viticultural climatic indexes as observed in the meteorological stations of Palomas (from 1994 to 2009) and Rivera (from 2001 to 2021).

Station	Vintage year	Code	HI value	CI value	DI value	$DI_{modified}$ value	HI class	CI class	DI class	ENSO phase
Palomas	1994	Pa94	2497	15.7	200	443	HI+2	CI-1	DI-2	Neutral
	1995	Pa95	2752	16.3	113	211	HI+2	CI-1	DI-1	El Niño
	1996	Pa96	2916	18.0	121	138	HI+2	CI-2	DI-1	La Niña
	1997	Pa97	2698	13.8	148	172	HI+2	CI+1	DI-1	Neutral
	1998	Pa98	2638	16.9	200	1069	HI+2	CI-1	DI-2	El Niño
	1999	Pa99	2981	18.5	8	13	HI+2	CI-2	DI+1	La Niña
	2000	Pa00	2859	15.6	74	104	HI+2	CI-1	DI-1	La Niña
	2001	Pa01	2812	19.4	200	250	HI+2	CI-2	DI-2	La Niña
	2002	Pa02	2644	19.6	200	327	HI+2	CI-2	DI-2	Neutral
	2003	Pa03	2694	17.2	200	983	HI+2	CI-1	DI-2	El Niño
	2004	Pa04	2724	16.4	49	123	HI+2	CI-1	DI+1	Neutral
	2005	Pa05	2724	16.7	68	103	HI+2	CI-1	DI-1	El Niño
	2006	Pa06	2797	16.5	-54	-13	HI+2	CI-1	DI+1	La Niña
	2007	Pa07	2911	18.4	200	588	HI+2	CI-2	DI-2	El Niño
	2008	Pa08	2703	16.4	155	470	HI+2	CI-1	DI-2	La Niña
	2009	Pa09	2748	16.8	200	361	HI+2	CI-1	DI-2	La Niña
Rivera	2001	Ri01	2714	19.6	200	265	HI+2	CI-2	DI-2	La Niña
	2002	Ri02	2699	20.0	200	396	HI+2	CI-2	DI-2	Neutral
	2003	Ri03	2689	17.2	200	828	HI+2	CI-1	DI-2	El Niño
	2004	Ri04	2693	16.6	82	207	HI+2	CI-1	DI-1	Neutral
	2005	Ri05	2779	16.9	68	129	HI+2	CI-1	DI-1	El Niño
	2006	Ri06	2840	17.2	-20	65	HI+2	CI-1	DI+1	La Niña
	2007	Ri07	2820	18.4	200	574	HI+2	CI-2	DI-2	El Niño
	2008	Ri08	2802	17.2	7	130	HI+2	CI-1	DI+1	La Niña
	2009	Ri09	2799	17.3	158	229	HI+2	CI-1	DI-2	La Niña
	2010	Ri10	2713	17.7	171	1017	HI+2	CI-1	DI-2	El Niño
	2011	Ri11	2827	16.5	-3	-3	HI+2	CI-1	DI+1	La Niña
	2012	Ri12	2828	16.5	87	114	HI+2	CI-1	DI-1	La Niña
	2013	Ri13	2667	14.6	165	367	HI+2	CI-1	DI-2	Neutral
	2014	Ri14	2815	15.2	200	494	HI+2	CI-1	DI-2	Neutral
	2015	Ri15	2771	17.4	177	341	HI+2	CI-1	DI-2	El Niño
	2016	Ri16	2637	16.5	187	809	HI+2	CI-1	DI-2	El Niño
	2017	Ri17	2747	16.6	200	393	HI+2	CI-1	DI-2	La Niña
	2018	Ri18	2721	15.7	50	131	HI+2	CI-1	DI-1	La Niña
	2019	Ri19	2648	16.3	124	525	HI+2	CI-1	DI-1	El Niño
	2020	Ri20	2868	18.2	20	285	HI+2	CI-2	DI+1	Neutral
	2021	Ri21	2689	17.2	200	422	HI+2	CI-1	DI-2	La Niña

HI – heliothermal index; CI – cool night index; DI – dryness index;
ENSO – El Niño-Southern Oscillation; HI+2 – warm; CI-2 – warm nights;
CI-1 – temperate nights; CI+1 – cool nights; DI-2 – humid; DI-1 sub-humid; DI+1 – dry.

Source: Elaborated by the authors.

Considerable climate variability was observed in all the indexes in both stations (Tables 2 and 3). The HI always fitted within the same class (HI+2) in both stations but presented high amplitude of values. The predominant CI class was CI-1 (temperate nights), followed by CI-2 (warm nights) in almost one third of the cases at Palomas. Only one exceptional case of CI+1 (cool nights) happened. In contrast, the index showing the highest variability was the DI, which was fitted with considerably high frequency within three classes (out of the four existing DI classes). These oscillating DI results are highly impacting for the vitivinivultural sector that faces the alternation between humid, sub-humid and dry years. Even so, more than 80% of the production cycles were sub-humid and humid.

Table 3 – Relative frequency of occurrence of the viticultural climate classes in the stations of Palomas (from 1994 to 2009) and Rivera (from 2001 to 2021).

Station and number of production cycles under study	HI class	Relative frequency of occurrence	CI class	Relative frequency of occurrence	DI class	Relative frequency of occurrence
Palomas (16 production cycles)	HI+2	16/16 (100%)	CI-2	5/16 (31.3%)	DI-2	8/16 (50%)
			CI-1	10/16 (62.5%)	DI-1	5/16 (31.3%)
			CI+1	1/16 (6.3%)	DI+1	3/16 (18.8%)
Rivera (21 production cycles)	HI+2	21/21 (100%)	CI-2	4/21 (19%)	DI-2	12/21 (57.1%)
			CI-1	17/21 (81%)	DI-1	5/21 (23.8%)
			CI+1	0/21 (0%)	DI+1	4/21 (19%)

HI – heliothermal index; CI – cool night index; DI – dryness index; HI+2 – warm; CI-2 – warm nights; CI-1 – temperate nights; CI+1 – cool nights; DI-2 – humid; DI-1 sub-humid; DI+1 – dry.

Source: Elaborated by the authors.

The frequency analysis of the different classes occurring in years belonging to the same ENSO phase (Table 4) revealed some patterns. The HI was not included in this frequency analysis because, as already shown previously (Tables 2 and 3), the class HI+2 was observed in 100% of the cases in both stations. For the CI, in the three ENSO phases in both stations the class CI-1 (temperate nights) occurred with the highest frequency. For the DI, the results of the two stations were quite comparable and conclusive. The class DI-2 was the most prevalent in all the cases, without exception. Therefore, humid conditions are the most commonly found in that region. Without exception, when the El Niño events were not associated with the most common DI class (DI-2, humid) they were associated with next class (DI-1, sub-humid). On the other hand, La Niña events showed the lowest frequency of DI-2 (humid) and the highest frequency of DI+1 (dry) among the ENSO phases.

In the PCAs constructed with the values of the indexes calculated for the station of Palomas (Figure 1), the indexes presented good projections but low correlations among them (Figure 1b). The index with the highest projection on the first dimension was the HI, which is hence a main variable to explain the variability of the data. The grouping and segregation of the production cycles (Figure 1a) indicated strong tendencies according to the three ENSO phases. El Niño and neutral events were more similar and distant from La Niña events. When the $DI_{modified}$ was used (Figure 1c and 1d), the segregation between the three ENSO phases was more evident. El Niño and La Niña became better separated, mainly on the axis of the variable $DI_{modified}$. In fact, this variable is supposed to better express water surpluses in the vineyard (Alves; Tonietto, 2018). Therefore, the hydric conditions expressed by this index were strongly influenced by the ENSO. The variable CI showed the highest and lowest values in neutral years. Nevertheless, the neutral years had on average low CI values, as three out of four years (75%) had CI values below the local overall average.

Table 4 – Relative frequency of occurrence of the viticultural climate classes in the production cycles under the influence of the each ENSO phase in the stations of Palomas (from 1994 to 2009) and Rivera (from 2001 to 2021).

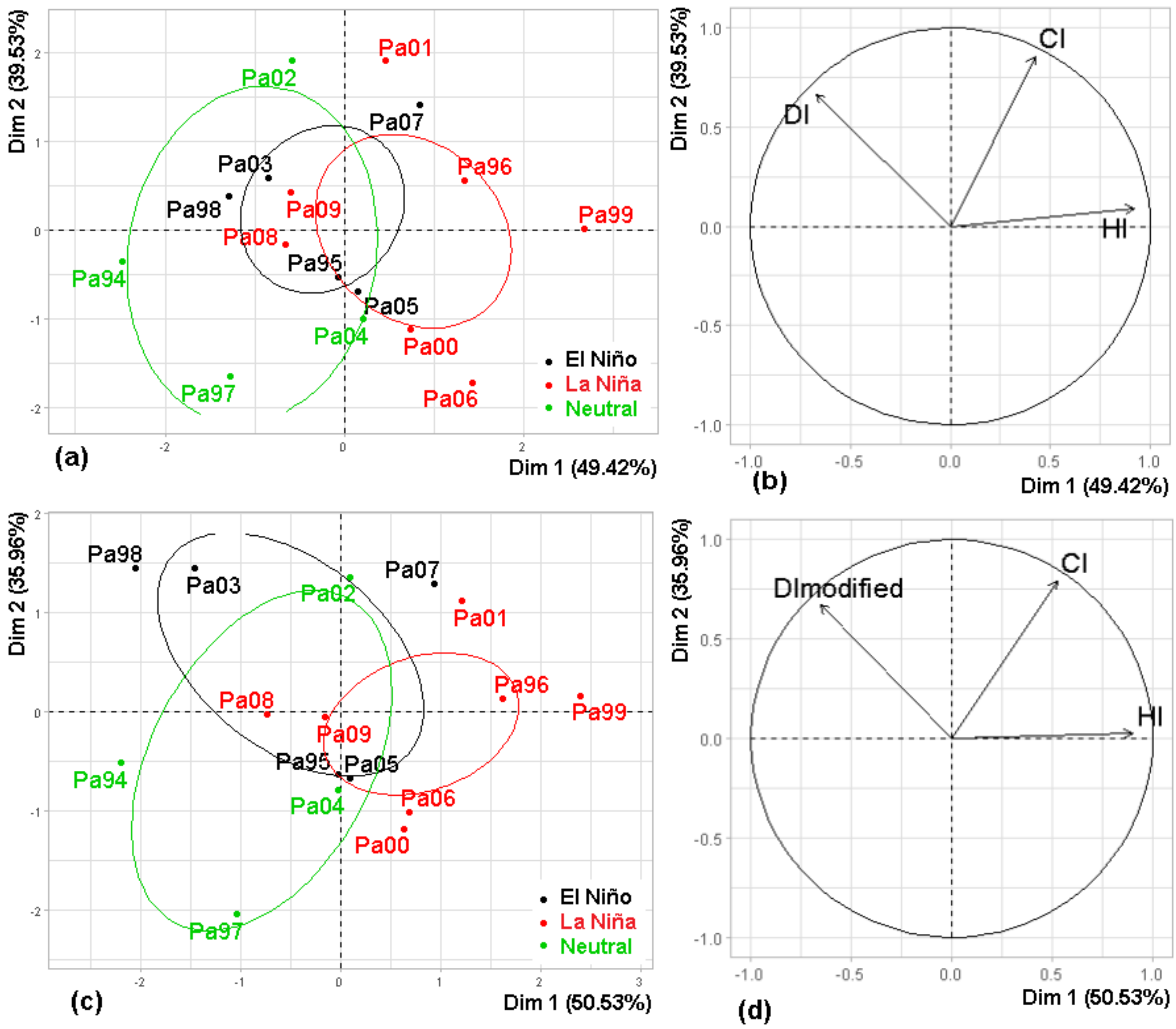
Station and number of production cycles under study	ENSO phase	Number of ENSO events	CI class	Frequency of occurrence	DIclass	Frequency of occurrence
Palomas (16 production cycles)	El Niño	5	CI-2	1/5 (20%)	DI-2	3/5 (60%)
			CI-1	4/5 (80%)	DI-1	2/5 (40%)
			CI+1	0/5 (0%)	DI+1	0/5 (0%)
	Neutral	4	CI-2	1/4 (25%)	DI-2	2/4 (50%)
			CI-1	2/4 (50%)	DI-1	1/4 (25%)
			CI+1	1/4 (25%)	DI+1	1/4 (25%)
	La Niña	7	CI-2	3/7 (42.9%)	DI-2	3/7 (42.9%)
			CI-1	4/7 (57.1%)	DI-1	2/7 (28.6%)
			CI+1	0/7 (0%)	DI+1	2/7 (28.6%)
Rivera (21 production cycles)	El Niño	7	CI-2	1/7 (14.3%)	DI-2	5/7 (71.4%)
			CI-1	6/7 (85.7%)	DI-1	2/7 (28.6%)
			CI+1	0/7 (0%)	DI+1	0/7 (0%)
	Neutral	5	CI-2	2/5 (40%)	DI-2	3/5 (60%)
			CI-1	3/5 (60%)	DI-1	1/5 (20%)
			CI+1	0/5 (0%)	DI+1	1/5 (20%)
	La Niña	9	CI-2	1/9 (11.1%)	DI-2	4/9 (44.4%)
			CI-1	8/9 (88.9%)	DI-1	2/9 (22.2%)
			CI+1	0/9 (0%)	DI+1	3/9 (33.3%)

HI – heliothermal index; CI – cool night index; DI – dryness index; ENSO – El Niño-Southern Oscillation; CI-2 – warm nights; CI-1 – temperate nights; CI+1 – cool nights; DI-2 – humid; DI-1 sub-humid; DI+1 – dry.

Source: Elaborated by the authors.

In the PCAs constructed with data from Rivera (Figure 2), the patterns observed were similar to those from Palomas. The loading plots (Figure 2b and 2d) showed that both HI and DI (or $DI_{modified}$) - well projected in the first dimension - were main variables to explain the variability in the data. These two variables also presented considerably high inverse relationship. The CI did not correlate well with the other variables but was highly determining for the second dimension, what expressed still around 35% of the variability in the data. The scoreplots (Figures 2a and 2c), as already observed in the PCAs constructed with data from Palomas, confirmed the segregation patterns associated with the polarization between El Niño and La Niña. El Niño events typically presented higher DI or $DI_{modified}$ and lower HI values, which is the exactly opposite observed for La Niña events. When the DI was used (Figures 2a and 2b), the neutral years were more disperse and confused among the years belonging to the other ENSO phases. On the other hand, the use of $DI_{modified}$ (Figures 2c and 2d) allowed a more clear segregation between the three ENSO phases. As also observed in the analysis of data from the other station, neutral years were slightly closer to El Niño years and presented high amplitude of CI values, including their absolute maximum and minimum.

Figure 1 – Score plots (a and c) and loading plots (b and d) of the principal component analysis constructed with the values observed for heliothermal index (HI), cool-night index (CI), and dryness index (DI) - a and b - and for heliothermal index (HI), cool-night index (CI), and modified dryness index ($DI_{modified}$) - c and d - in the stations of Palomas (from 1994 to 2009). Pa94 – Palomas, 1994; Pa95 – Palomas, 1995; Pa96 – Palomas, 1996; Pa97 – Palomas, 1997; Pa98 – Palomas, 1998; Pa99 – Palomas, 1999; Pa00 – Palomas, 2000; Pa01 – Palomas, 2001; Pa02 – Palomas, 2002; Pa03 – Palomas, 2003; Pa04 – Palomas, 2004; Pa05 – Palomas, 2005; Pa06 – Palomas, 2006; Pa07 – Palomas, 2007; Pa08 – Palomas, 2008; Pa09 – Palomas, 2009.



Source: Elaborated by the authors.

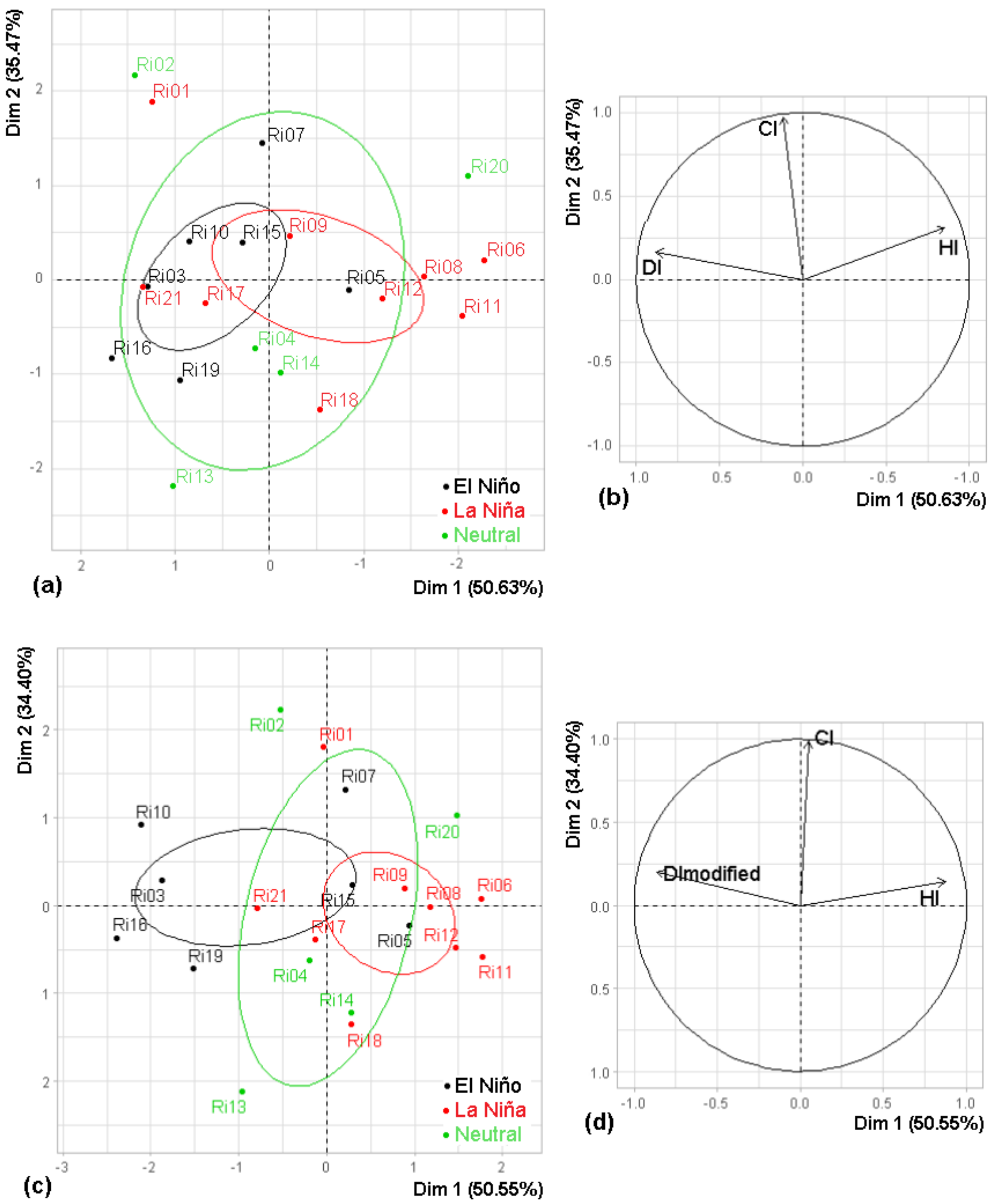
The PCAs showed that the variable $DI_{modified}$ was more determining for the segregation of ENSO events than the variable DI and is thus more representative for understanding the variability of the local climate. Another important aspect is that, in the PCAs, this variable allowed to segregate the most extreme El Niño events (those with the highest positive temperature oscillations in the Pacific Ocean surface waters), namely: 98 and 03 (Figure 1) and 03, 10 e 16 (Figure 2). It means that these most extreme positive temperature anomalies in the Pacific Ocean surface waters were well correlated with the most extreme water surpluses in the region under study. These vintages were also among those with the worst crop failures in the vineyards of Santana do Livramento (Kaltbach *et al.*, 2023). These crop cycles also presented HI values below the mean and median of the datasets. In summary, these strong El Niño events were negative for grape maturation both because of hydric and thermic aspects.

The PCAs also indicated that the variability of continuous values of HI was highly determining for characterizing and explaining the climate variability. Nevertheless, that had not been expressed by the discrete data – class intervals – that classified the production cycles always within only one HI class (HI+2, warm).

Most of the climate variability observed in the region under study could be correlated to the ENSO. El Niño events tend to be the most challenging for viticulture as they present more humid conditions and lower availability of thermal energy. The excess of water in the vineyard tend to increase the pressure of fungal diseases such as mildew, the most important disease attacking vineyards in the Brazilian humid regions (Nachtigal; Mazzarolo, 2008). The lowest availability of thermal energy also tends to retard the phenological development (Cortázar-Atauri *et al.*, 2017; Ollat *et al.*, 2016; Parker *et al.*, 2020). Additionally, the water surplus causes a dilution effect on the photoassimilates accumulated in the berries, which delays even more the harvest dates (Bender *et al.*, 2021). The combination of these factors results in longer production cycles (later harvest dates), with higher demands, mainly with respect to phytosanitary treatments – until the grapes present a sufficient technological maturation level for vinification. Commonly, the excessively humid conditions and its imposed high risk of phytosanitary issues force the anticipation of harvesting, when the ideal heat sum for the desirable grape maturation level has not been reached yet. Therefore, in Santana do Livramento, in these years, there is a tendency for higher costs and lower grape enological quality, as both grape production and sugar levels tend to be reduced by El Niño events (Kaltbach *et al.*, 2022, 2023).

Under La Niña influence, typically, the meteorological characteristics were opposite to those observed during El Niño influence – at least within the range observed for each index. Even though several La Niña years were humid, there were no cases of extreme water surplus (e.g. $DI_{modified} > 800$mm) such as those observed in some El Niño years (98, 03, 10 and 16). So, in general, La Niña provides the most favorable conditions for reducing the incidence of fungal diseases (Nachtigal; Mazzarolo, 2008), increasing the accumulation of photoassimilates in the berries (Bender *et al.*, 2021) and shortening the crop cycle (Cortázar-Atauri *et al.*, 2017; Ollat *et al.*, 2016; Parker *et al.*, 2020). The combination of less water and more thermal energy available in the vineyard tends to result in faster grape maturation and less but more effective phytosanitary interventions.

Figure 2 – Score plots (a and c) and loading plots (b and d) of the principal component analysis constructed with the values observed for heliothermal index (HI), cool-night index (CI), and dryness index (DI) - a and b - and for heliothermal index (HI), cool-night index (CI), and modified dryness index ($DI_{modified}$) - c and d - in the stations of Rivera (from 2001 to 2021). Plots a and b display unconventional reverse horizontal axis values to improve graphical comparisons. Ri01 – Rivera, 2001; Ri02 – Rivera, 2002; Ri03 – Rivera, 2003; Ri04 – Rivera, 2004; Ri05 – Rivera, 2005; Ri06 – Rivera, 2006; Ri07 – Rivera, 2007; Ri08 – Rivera, 2008; Ri09 – Rivera, 2009; Ri10 – Rivera, 2010; Ri11 – Rivera, 2011; Ri12 – Rivera, 2012; Ri13 – Rivera, 2013; Ri14 – Rivera, 2014; Ri15 – Rivera, 2015; Ri16 – Rivera, 2016; Ri17 – Rivera, 2017; Ri18 – Rivera, 2018; Ri19 – Rivera, 2019; Ri20 – Rivera, 2020; Ri21 – Rivera, 2021.



Source: Elaborated by the authors.

That makes it possible to keep the fruits longer in the plant, in order to achieve higher maturation levels. Therefore, in these years, costs tend to be lower and the adequate enological grape quality tends to be achieved more assertively. In fact, in Santana do Livramento, grape production and sugar levels tend to be higher in La Niña events (Kaltbach *et al.*, 2022, 2023). It is important to emphasize that most of the highest HI values were observed in La Niña events, which imposes higher risk of heat stress, especially in cultivars more sensitive to this.

In neutral years, the values observed for DI and HI were mostly intermediate to those observed in the warm and cold phases of the ENSO. Neutral years were more similar to El Niño years but were never extremely humid as strong El Niño years. Therefore, in Santana do Livramento, in neutral years, crop failures are unusual (Kaltbach *et al.*, 2023) and sugar accumulation is not severely impaired by weather conditions (Kaltbach *et al.*, 2022). On the other hand, the highest and lowest CI values were observed under neutral conditions, which increases the unpredictability of night temperatures in these cases, which might be even more risky for early cultivars (maturating closer to the summer solstice).

Considering the typical variability of the viticultural climate of the region under study, it is possible to conclude that more consistent results along the vintages must be attained with cultivars which present characteristics such as: lower susceptibility to fungal diseases occurring under humid conditions; higher tolerance against heat stress; and adequate maturation at conditions of high day and night temperature. The knowledge about climate variability is fundamental for the vitivinivulture production chain. Since the three ENSO phases present tendencies, monitoring the occurrence of them is strategic for better planning and managing the production cycles and mitigating losses. For example, another study (Kaltbach *et al.*, 2023) has already pointed out that it is possible to foresee an upcoming strong El Niño event still during winter, by monitoring the temperature of the Pacific Ocean surface waters. In these cases, many measures can still be taken, such as: financial planning; purchase of products for phytosanitary treatments; hiring of adequate crop insurance; adequate management practices since winter pruning, in order to promote better air and light flux in the vineyard; and rigorous phytosanitary treatments since the beginning of the crop cycle.

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