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Soil and climate effects on winter wine produced under the tropical environmental conditions of southeastern Brazil

Mariana Gabriele Marcolino Gonçalves[1], Luciana Alves Caldeira Brant[2], Renata Vieira da Mota[3], Isabela Peregrino[3], Claudia Rita de Souza[3], Murillo de Albuquerque Regina[3], Tatiele Fruett[4], Alberto Vasconcellos Inda[4], Nilton Curi[1] and Michele Duarte de Menezes[1]

[1] Department of Soil Science, Federal University of Lavras, 37200-000, Lavras, MG, Brazil
[2] Department of Agriculture, Federal University of Lavras, 37200-000, Lavras, MG, Brazil
[3] Agricultural Research Agency of the State of Minas Gerais, Experimental Center of Caldas, Santa Cruz Ave., 500, 37780-000, Caldas, MG, Brazil
[4] Department of Soil Science, Federal University of Rio Grande do Sul, Bento Gonçalves Ave., 7712, 91540-000, Porto Alegre, RS, Brazil

*correspondence:
michele.menezes@ufla.br

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ABSTRACT

Southeastern Brazil is an emergent region in terms of the production of high-quality fine wines. To contribute to typicity assessment, the soils (morphology, mineralogy, chemical and physical analyses), parent material (geologic maps and portable X-ray fluorescence spectrometry) and climate (temperature and precipitation) were characterized in seven vineyards located in the state of Minas Gerais and São Paulo, Brazil, by carrying out state-of-the-art terroir analysis and assessing the environmental variations of the study sites. A soil profile was described and sampled in the central part of each vineyard. Principal Component Analysis (PCA) biplots were used to analyze the relationships between these factors and the composition of wines (2016, 2017 and 2018 harvests) produced from Syrah in commercial vineyards in different municipalities of Três Corações (TC), Cordislândia (COR), Andradas (AND), São Sebastião do Paraíso (SSP), Três Pontas (TP), Espírito Santo do Pinhal (PIN) and Itobí (ITO). The vineyards were grouped according to soil and climate characteristics. Group A was composed of COR, AND and PIN vineyards, which exhibited the highest correlation with soil Al^{3+} content and accumulated rainfall. The group's wines had the lowest ash alkalinity, total polyphenol index (TPI) and pH values and the highest fixed acidity. Group B consisted of the TP and TC vineyards, which had the highest soil organic matter and boron contents and the highest thermal amplitude with similar values (15.4 °C in TC and 15.2 °C in TP); their wines showed average composition. Group C comprised ITO alone, which was characterized by the shallowest and least developed soils. Its wine had the highest flavonol content and high dry extract, color intensity, TPI, alcohol content and sugar values. Group D contained the SSP vineyard, in which the soil subsurface horizons were correlated with the highest wine pH. Late harvest in this vineyard caused the most dehydration of grapes and consequent concentration of most wine compounds (human effect on terroir). The terroir information produced in this study adds substantial value to the wines produced under the tropical environmental conditions of southeastern Brazil, for which such studies are very rare. By characterizing the natural factors (soil, soil parent material and climate) and human factors (vineyard management and wine characteristics) related to terroir, this study can also provide historical information about the wine from this emergent region (the historical factors). In addition, its results can be used to guide producers in their choice of vineyard cultivation sites according to preference in wine composition.

KEYWORDS: Pedology, wine composition, soil parent material, terroir, principal component analysis

INTRODUCTION

Southeastern Brazil is an emergent region in terms of the production of high-quality fine wines (Favero *et al.*, 2011). The evolution of production is closely related to the vineyard management approach known as 'double pruning', which allows grapes to be harvested during winter (Regina *et al.*, 2011). Two prunings are performed per year: the first at the end of the winter season (August or September) for shoot vegetative development, and the second - known as 'yield pruning' - in January in lignified brunches to ensure the grapes are ready for harvest during the winter period. The climatic conditions of the winter period (from June to September) lead to a greater accumulation of phenolic compounds and sugars compared to the summer harvest (from December to March), which is the traditional time to harvest grapes in Brazil (Amorim *et al.*, 2005; Favero *et al.*, 2011; Mota *et al.*, 2011). Wines from this region are known as "Winter Wines", because of the grape harvest season. The Syrah variety has proven to be the most suited to the regional climatic conditions (Amorim *et al.*, 2005; Favero *et al.*, 2011).

The well-known terroir terminology has traditionally been used to describe the notion of agricultural sites in a geographical area that share similar climate and soil, as well as management practices. The combination of these conditions contributes to creating products with unique characteristics (van Leeuwen and Seguin, 2006; Fayolle *et al.*, 2019; Deloire *et al.*, 2005). The effect of soil and climate on grapevine development and the composition of grapes or wines has been demonstrated in well-known viticultural regions of the world, such as in Italy (Priori *et al.*, 2019), Canada (Kotsaki *et al.*, 2019), Spain (Perez-Alvarez *et al.*, 2015), Portugal (Prata-Sena *et al.*, 2018) and China (Wang *et al.*, 2015). While some regions have defined, understood and developed their terroirs over the centuries (e.g., the Bordeaux (Renouf *et al.*, 2010; Seguin, 1986) and Champagne (Deloire *et al.*, 2005; White, 2003) regions in France, Campania in Italy (Bonfante *et al.*, 2011) and Rioja in Spain (Seguin, 1986), new regions face the challenge of finding the most adapted varieties and the best management practices to define their typicities (Jones *et al.*, 2004).

Macroclimate (regional) and microclimate (local climate in the fruit zone) conditions greatly affect vine growth, yield and grape and wine quality attributes (van Leeuwen and Seguin, 2006). Soil attributes are essential for vines under tropical conditions, especially in terms of their effect on local water availability. In addition, soils play an important role in providing nutrients for plants, affecting the vigor of grapevines (van Leeuwen *et al.*, 2018; Morlat and Bodin, 2006), which is in turn directly related to the composition of the berries and wines (Cortell *et al.*, 2008). Soils that do not restrict water availability can result in the production of wines with lower added value in relation to the sale price (Renouf *et al.*, 2010). Low soil water supply results in less vigorous and productive grape vines high in berry anthocyanin and tannin content, which is beneficial for the wine (Van Leeuwen *et al.*, 2009); conversely, the sugar content, polyphenols indexes and grape weight of vines in Italy was positively affected by the greater availability of water in the soil (Costantini, 2021). In both latter two studies, the authors proposed that the higher availability of water in soils may have favored the absorption of nitrogen by the plants. Morlat and Bodin (2006) compared soils which had undergone different degrees of weathering and found that less weathered soils increased positive effects on wine quality: smaller berries, higher anthocyanin content and lower total acidity.

Different combinations of soil morphology and physical aspects lead to different soil responses; this is important given the role that the soil microclimate plays in the classification of wine terroir. Soil water availability has been found to have a major effect on terroir (van Leeuwen *et al.*, 2018), especially in local-scale analysis (Swinchatt *et al.*, 2018) and in regions with characteristically dry periods, as in Southern Brazil. Soil water retention depends on soil texture, as well as on soil mineralogy, depth, structure, and topography (van Leeuwen *et al.*, 2004; Resende *et al.*, 2014). Some of those attributes are also criteria for soil classification (Soil Survey Staff, 2014), serving as a basis for the interpretation of water availability and the growth behavior of plant roots.

Several agronomical and physiological studies have been carried out on crops subject to the double pruning management practice (Amorim *et al.*, 2005; Favero *et al.*, 2011) and on the effects of using different rootstocks (Souza *et al.*, 2015; Dias *et al.*, 2017), as well as the effects of the growing season (Favero *et al.*, 2011) on grape quality (Favero *et al.*, 2008) and the aromatic profile of wines (Mota *et al.*, 2021). However, few studies have characterized vineyard soil and climate – important for the improvement of the wine typicity protocol - especially in tropical developing countries (Santos *et al.*, 2018). Thus, the objectives of this study were to characterize the soils and climate on a local scale and to examine their relationship with the composition of Winter Wines produced in seven commercial vineyards of the Syrah cultivar under the tropical environmental conditions of southeastern Brazil.

MATERIALS AND METHODS

1. Study areas

The study was carried out in seven commercial vineyards of Syrah cultivars in southeastern Brazil in the municipalities of Três Corações (TC), Cordislândia (COR), Andradas (AND), São Sebastião do Paraíso (SSP) and Três Pontas (TP) in Minas Gerais and of Espírito Santo do Pinhal (PIN) and Itobí (ITO) in São Paulo (Figure 1). A soil profile was carefully selected and morphologically described. Soil samples were taken from the central part of each vineyard to represent each area. The vineyards are between 10 and 15 years old. Their shoots are grown vertically with bilateral cordons at a density of 4000 plants/ha^{-1}. A double pruning management

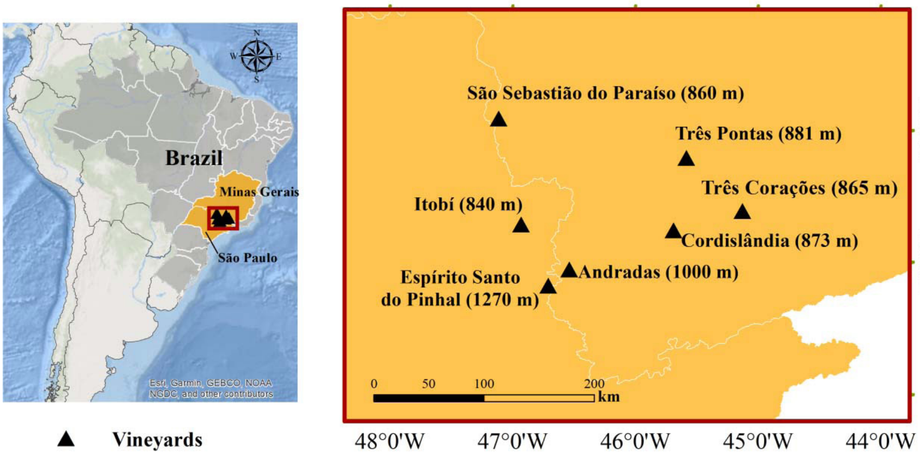

FIGURE 1. Vineyard locations with names of the nearest municipalities and their respective elevations (m) in the states of Minas Gerais and São Paulo, Brazil.

system is used as described in Favero *et al.* (2011). The crop practices usually applied by each winegrower in the vineyards, including those related to fertilisations and harvest, were carried out.

2. Soil and climate characterisation

The soil profiles were described morphologically according to Schoeneberger *et al.* (2012), and the soils were classified according to US Soil Taxonomy (Soil Survey Staff, 2014). Physical, chemical, and mineralogical analyses were carried out on samples of the main soil horizon of each profile. The following physical analyses were performed or calculated: quantification of the gravel proportion, particle-size distribution involving vertical shaking, and chemical (0.1 mol L^{-1} NaOH) dispersion on the air-dried fine earth (ADFE) portion (< 2.0 mm) by the pipette method (Gee and Bauder, 1979). From these analyses it was possible to calculate the silt/clay ratio, an important metric for soils under tropical conditions that expresses degree of weathering (the higher the value, the less weathered the soil).

The following chemical analyses were carried out: pH in water, pH in 1.0 mol L^{-1} KCl; available P and K extracted using Mehlich-1 (Mehlich, 1953); exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} extracted with 1.0 mol L^{-1} KCl (McLean *et al.*, 1958); potential acidity ($H^+ + Al^{3+}$) extracted using 0.5 mol/L calcium acetate at pH 7.0 (Teixeira *et al.*, 2017); soil organic matter (SOM) by the Walkley and Black (1934) method; and remaining P (Rem-P) according to Alvarez *et al.* (2000). Effective cation exchange capacity at soil pH (ECEC), cation exchange capacity at pH 7.0 (CEC pH 7.0), base saturation (BS) and aluminum saturation (AS) were then calculated. The soil water content at field capacity and permanent wilting point were estimated according to the equation developed by Arruda *et al.* (1987) based on silt and clay content (%):

$$\text{Field capacity} = 3.1 + 0.629x - 0.0034(clay + silt)^2$$

$$\text{Permanent wilting point} = \frac{398.9(clay + silt)}{1308.1 + (clay + silt)}$$

Thus, the available water capacity was calculated according to Reichardt (1985) (soil water content at field capacity minus permanent wilting point). The concentration of crystalline Fe oxides (Fe extracted using Dithionite citrate - Fe_d) (Mehra and Jackson, 1958) and Fe oxides with a low degree of crystallinity (Fe extracted with ammonium oxalate - Fe_o) (McKeague and Day, 1966) was determined to complement the assessment of the degree of soil weathering (Inda Junior and Kämpf, 2003).

Soil parent material was initially assessed from the indications contained in geological maps of the states of Minas Gerais (CPRM, 2003) and São Paulo (Peixoto, 2010). This information was refined with information from the literature (Mancini *et al.*, 2019) which was compared with the contents of elements and oxides determined by portable X-ray fluorescence spectrometry and mineralogy of the soil fractions as described below. The elemental and oxide contents in the soil samples were determined by portable X-ray fluorescence (pXRF) spectrometry (Bruker S1 Titan LE model). The samples were scanned in triplicate for 60 s using the Trace mode of the Geochem software. The pXRF was calibrated using scanning standard reference materials 2710a and 2710b and a check sample (CS). The minerals present in the clay, silt and fine sand fractions of the soil B horizons were identified via X-ray diffractometry using a Bruker D2-Phaser instrument equipped with a Lynxeye™ fast linear detector. The XRD patterns were processed with the software Diffrac.Suite™. The diffractometer used CuKα radiation (λ = 1.5418 Å) passing through a Ni filter, with a current intensity of 10 mA and a power of 30 kVA. Analyses were conducted on non-oriented slides of fine sand, silt and clay fractions (°2θ range 4-50) and an Fe-concentrated clay fraction (°2θ range 15-50) at a step size of 0.01 °2θ/s. The XRD patterns were obtained with the Diffract Suite Eva software. Interpretation of the spectra followed Brindley and Brown (1980).

The climatic characterisation of the grape maturation period (May to July) was based on average historical data (1982 to 2012) obtained from Climate.data.org (https://pt.climate-data.org/). Using 1.8 billion data points, a global map without gaps was generated in a 0.1 – 0.25 grade. This climate model was based on the European Centre for Medium Range Forecasts (ECMWF) dataset.

3. Wine laboratory analyses

The grapes harvested from vineyards were vinified and their composition was evaluated for three harvests: 2016, 2017 and 2018. Total phenols were analysed using the Folin-Ciocalteau method, which is based on a standard curve of gallic acid (Bergqvist *et al.*, 2001). Ash content was determined using the gravimetric method and ash alkalinity via the titrimetric method (Blouin, 1992). Anthocyanin content was obtained using the differential pH method (Giusti and Wrolstad, 2001), with the results expressed in mg malvidin-3-glycoside per litre of wine. The dry extract was determined according to the AOAC method 920.62 (AOAC, 1995). Phenols were quantified according to Amerine and Ough (1980), and the flavanol content was determined according to Ribéreau-Gayon *et al.* (2006). Colour intensity was determined from the sum of absorbance at 420, 520 and 620 nm (Curvelo-Garcia, 1988). The total polyphenol index (TPI) was determined at 280 nm in a UV/VIS spectrophotometer (Shimadzu UV-1800). Fixed acidity was measured according to OIV (2009) and pH using a digital potentiometer (Micronal model B 474). Alcohol content by volume was determined using a hydrostatic scale (Super Alcomat, Gibertini) after wine distillation (Super DEE Gibertini digital distilling unit) and sugar content was determined via the Fehling method (Brasil, 1986).

4. Statistical analysis

The relationships between pedological and climatic characteristics and the average composition of the wines from all three vintages (2016, 2017 and 2018) were assessed by principal component analysis (PCA). Since a myriad of soil and climate attributes could affect wine composition to varying degrees, the PCA biplot was performed with numerical attributes in order to reduce dimensionality, extract the dominant patterns and find relationships within the dataset. In order to better understand the typicity of the local wine, a large amount of information was used for the PCA to identify the underlying dominant features (Barth *et al.*, 2021). The dataset was pre-treated to deal with the differences in measurement units by dividing it by the root mean square. PCA was performed on two different datasets for i) A-horizon soil attributes and climate data, and ii) B-horizon soil attributes and climate data. Most management inputs have traditionally focused on surface soil fertility, while as B horizon expresses pedogenetic processes it is generally not chemically corrected. However, the B horizon is also important as the root system takes up water and nutrients from it, mainly during extensive dry periods. Both horizons are important for understanding the effect of soils on wine composition. In both datasets, soil information was used as active variables and wine composition was plotted over it as supplementary variables (FactoMineR package, version 1.42) in R software (R Development Core Team). Supplementary variables do not contribute to the construction of the principal components; they are also known as illustrative variables and help in interpreting the plot.

RESULTS AND DISCUSSION

1. Soil types and physical properties

Four soil types were identified in the vineyards (Table *1*): Acrudox and Hapludox → Hapludult → Eutrudept (Figure 2). Following this chronological sequence, soil depth decreases and the structure shape varies from granular to blocky. Consequently, there is a decrease in soil water storage and plant root penetration. Soil texture classes ranged from clay to sandy clay loam (Table *1*), reflected by the variation in the parent material and the degree of weathering (Resende *et al.*, 2014).

The most weathered soils (Acrudox, TC and COR; Hapludox, TP) have homogeneous texture classes throughout the soil profile. The highest clay contents in the A horizon occur in the TC and TP soils. In the B horizon, the strong soil aggregation in a granular shape increases macroporosity, pore continuity (Ferreira *et al.*, 1999) and water drainage. In contrast, good porosity, along with soil thickness, favours root system growth (Resende *et al.*, 2014), preventing water deficit in grapevines. Indeed, the values of leaf water potential indicate a lack of severe water deficiency in such soils (Brant *et al.*, 2021).

Hapludults normally exhibit textural differentiation in that the clay content is lower at the surface and higher in the subsurface horizons. The high sand content of the A horizon contrasts with the block structure and clayey texture of the B horizon. In contrast to Acrudoxes and Hapludoxes, the higher the clay content of Hapludults, the lower its permeability. Eutrudepts are the shallowest of the four soil types; their limited thickness and their block structure in the B horizon make it difficult for vines to deepen their root system, significantly decreasing water availability (Resende *et al.*, 2014).

In addition to the relatively high content of sand at the surface of the AND and PIN soils, they both contained gravel at all depths, as did ITO, which contributes to a reduction in water storage (Saxton and Rawls, 2006). This is an important characteristic of vineyards, as it can reduce water storage at greater depths (Resende *et al.*, 2014) and thus lead to a certain water deficit for plants, especially during dry periods. Similarly, gravely soils of the viticultural region of Bordeaux traditionally produce high-quality wines (cru classé), since gravels promote better soil drainage (Seguin, 1986).

TABLE 1. Physical and morphological soil properties.

	Horizon	Clay	Silt	Total sand	Coarse sand	Fine sand	Silt/Clay	Gravel	Texture class	FC[1]	PWP[2]	AWC[3]	Structure shape of the B horizon
				dag kg^{-1}				g kg^{-1}			%		
ACRUDOX (TC)	Ap	50	26	24	8	16	0.52	-	Clay	31.27	21.90	9.36	granular
	Bo1	52	28	20	7	13	0.54	-	Clay	31.66	22.99	8.67	
	Bo2	58	21	21	7	14	0.36	-	Clay	31.57	22.72	8.85	
ACRUDOX (COR)	Ap	56	15	29	14	15	0.26	-	Clay loam	30.62	20.54	10.08	granular
	Bo1	69	9	22	11	11	0.13	-	Clay	31.48	22.45	9.03	
	Bo2	69	11	20	9	11	0.16	-	Clay	31.66	22.99	8.67	
HAPLUDULT (AND)	Ap	30	20	50	35	15	0.67	52	Sandy clay loam	26.05	14.69	11.36	blocky
	Bt1	53	11	36	26	10	0.21	25	Clay	29.43	18.61	10.82	
	Bt2	53	13	34	25	9	0.25	163	Clay	29.80	19.16	10.64	
HAPLUDULT (PIN)	Ap	40	9	51	38	13	0.23	36	Sandy clay	25.76	14.40	11.35	blocky
	Bt1	44	12	44	33	11	0.27	58	Clay	27.66	16.38	11.29	
	Bt2	50	12	38	28	10	0.24	96	Clay	29.03	18.05	10.98	
	BC	49	12	39	30	9	0.24	131	Clay	28.82	17.77	11.04	
EUTRUDEPT (ITO)	Ap	40	18	42	27	15	0.45	78	Clay	27.91	16.66	11.25	blocky
	Bw	38	21	41	26	15	0.55	109	Clay loam	28.38	17.22	11.16	
ACRUDOX (SSP)	Ap	38	24	38	7	31	0.63	1	Clay loam	29.03	18.05	10.98	granular
	Bo1	38	26	36	7	29	0.68	-	Clay loam	29.43	18.61	10.82	
	Bo2	40	27	33	6	27	0.68	-	Clay loam	29.98	19.44	10.54	
HAPLUDOX (TP)	Ap	50	28	22	6	16	0.59	-	Clay	31.48	22.45	9.03	granular
	Bo1	50	28	22	7	15	0.56	-	Clay	31.48	22.45	9.03	
	Bo2	50	30	20	5	15	0.60	-	Clay	31.66	22.99	8.67	

[1]FC: field capacity; [2]PWP: permanent wilting point; [3]AWC: available water capacity.

2. Soil fertility analyses

A broad variation in pH and fertility attributes was found at different depths and in different vineyards. In terms of its chemistry, the A horizon was found to be generally far more suitable for plants than the B horizon (higher pH, SOM, K, P, Ca^{2+} and Mg^{2+}) (Table *2*). It should be noted that previous land use in TP (horticulture) might be responsible for the higher K content. The COR soil had the highest CEC in both soil horizons. The soil pH in H$_2$O ranged from 4.5 in the Bt1 horizon of the PIN soil to 7.60 in the Ap horizon in the COR soil. In general, acidity is lower in A horizons than in B horizons, which was corroborated by both the lower values of Al^{3+} and the higher values of base saturation (BS) in the surface horizons. This is due to liming without incorporation, which is practised in vineyard areas. In addition, TC and SSP had low base saturation values for all soil depths, since 80 % is considered ideal for grapevine crops in the region studied (Ribeiro *et al.*, 1999).

Since SOM is the largest reservoir of N for plants and is even used as a basis for recommending nitrogen fertilisation in Brazilian soils (Cantarella, 2007), it is assumed in the present study that SOM content reflects N content. On this basis, the TC and COR soils showed the highest N content in the A and B horizons.

3. Soil mineralogical composition

Mineral identification by means of X-ray diffraction (XRD) was performed on the fine sand, silt and clay fractions (Figure 3) and on the Fe-concentrated clay fraction (Figure 4) of the B horizons. The only soils that had easily-weathered primary minerals (EWPM) beyond dominant quartz in the silt and fine sand fractions were AND and ITO (Figure 3). The presence of mica in the silt fraction of AND (Figure 3c), as well as orthoclase in the fine sand fraction of ITO (Figure 3e), indicate a soil K reserve, since K can be released from such minerals by weathering processes (Curi *et al.*, 2005).

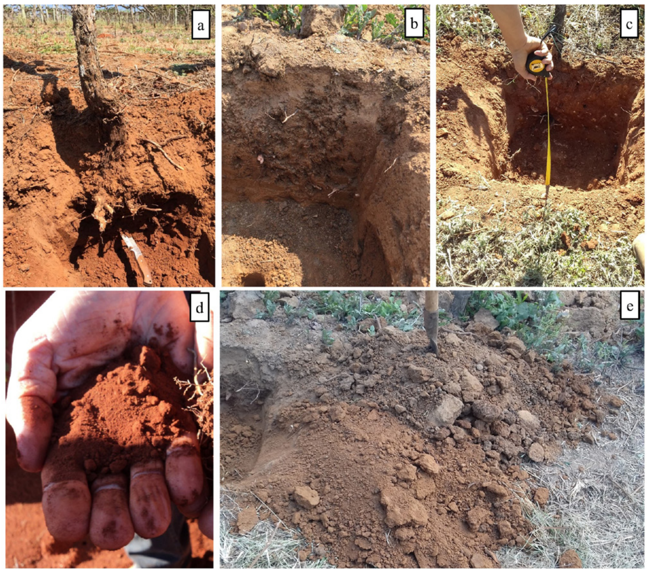

FIGURE 2. Soil profiles and soil structure types found in the vineyards: a) Acrudox in TC, COR and SSP (Três Corações, Cordislândia, São Sebastião do Paraíso respectively), with hydric behaviour similar to the Hapludox of TP; b) Hapludult in AND and PIN (Andradas and Espírito Santo do Pinhal); c) Eutrudept in ITO (Itobí); d) granular structure common to Acrudox and Hapludox; e) block structure that occurs in the Hapludults of AND and PIN and the Eutrudept of ITO. Modified from Gonçalves *et al.* (2020).

The Fe-oxide mineral concentration pre-treatment performed on the clay fraction of the soils (Figure *4*) enabled more accurate identification of these minerals, which tend to remain stable in soils, even under intense weathering-leaching conditions characteristic of tropical environments. A marked presence of the common Fe-oxide minerals hematite (Hm) and goethite (Gt) was found in all soils, and maghemite (Mh) was identified in the SSP, COR and TP soils (Figure 4). In addition to these Fe-oxide minerals, gibbsite (Gb) and kaolinite (Kt) were observed in all soils (Figure 3).

4. Parent material and oxides as indicators of the degree of soil weathering

The soils of this study were formed *in situ;* (geological alteration of the bedrock constitutes the soil parent material). This affects the soil characteristics that govern water dynamics, as well as nutrient availability (Bodin and Morlat, 2006; Huggett, 2006; Morlat and Bodin, 2006). In Brazil, pXRF spectrometry has been applied to determine soil parent materials with adequate accuracy (Mancini *et al.*, 2019), since traces of these materials are left in the soil. Figure 5 shows the total chemical composition of the soils obtained from the pXRF.

Five different parent materials were found in the vineyard soils. The parent material of TC is biotite-schist/gneiss, which is rich in a biotite that is an EWPM comprising K, Mg, Fe, Cu and Mn, among other elements. However, signs of its occurrence and the reserve of nutrients that it represents were not evident in the old soils. This is due to the intense degree of weathering-leaching, which is corroborated by the low Fe_o content (Inda Junior and Kämpf, 2003) (Table 3). Similar trends occurred for COR, AND, PIN and TP.

Pyroxene-granulite, the soil parent material of the COR vineyard, consists of a metamorphic rock containing mainly felsic minerals, such as quartz and feldspars, and the ferromagnesian mineral, pyroxene. Pyroxene is not very resistant to weathering and was therefore not observed in the mineralogical composition of the fine sand fraction of this soil (Figure 3b). The pXRF results showed low content of most trace elements and other elements originating from ferromagnesian minerals. SiO_2 and Al_2O_3 were predominant in this soil.

The parent material of the AND and TP soils is gneiss. This felsic rock mainly consists of SiO_2. High content of this oxide was found in both soils (Figure 5). The AND soil had higher Sr and K_2O contents, while the TP soil had the highest Al_2O_3. content. These elements and oxides are typical of gneiss.

The highest contents of K_2O, Ba, Ce, Mo, Nb, Rb, Y, Zn and Zr were found in the ITO soil, likely due to the low degree of weathering-leaching. Although the PIN and ITO soils were formed by the same type of parent material (granite), their chemical composition and physical properties were quite different due to the greater pedogenetic development of PIN.

The parent material of the SSP soil was a mixture of basalt (predominating) and sandstone. Basalt consists of ferromagnesian minerals such as pyroxene, hornblende, olivine and Ca-plagioclase. Total contents of Fe_2O_3, Cu, and Pb were greater in this soil. In addition, the SSP soil had the highest Fe content (determined by pXRF; Fe_d and Fe_o) out of all the soils (Table *3*).

The wine market is traditionally ruled by geology, with the description of the vineyards often found on wine bottles as a guide for consumers (Huggett, 2006). However, the soil-

TABLE 2. Soil fertility analyses of the vineyards.

	Hz	pH (KCl)	pH (H_2O)	ΔpH	K	P	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^++Al^{3+}	SB	ECEC	CEC	BS	AS	SOM	Rem-P	Zn	Fe	Mn	Cu	B	S
				mg kg^{-1}							cmol$_c$ kg^{-1}				%		dag kg^{-1}	mg L^{-1}			mg kg^{-1}			
ACRUDOX (TC)	Ap	4.8	5.6	-0.8	262.8	22.2	11.3	2.9	0.5	0.1	4.9	4.1	4.3	9.1	45.5	3.1	3.2	25.1	11.6	39.8	17.2	13.8	0.52	12.1
	Bo1	5.4	5.3	0.1	14.8	1.4	5.1	0.8	0.3	0.1	2.6	1.1	1.2	3.7	30.5	5.8	1.7	3.7	0.3	25.0	1.3	1.8	0.12	43.8
	Bo2	6.2	6.1	0.1	27.7	0.5	5.1	0.8	0.2	0.0	1.8	1.0	1.0	2.8	36.2	0.0	1.0	2.9	0.1	15.0	0.8	1.3	0.12	38.7
ACRUDOX (COR)	Ap	6.8	7.6	-0.8	247.0	44.1	10.3	7.7	2.8	0.1	1.4	11.1	11.2	12.5	89.1	0.5	3.6	20.9	16.1	25.8	20.8	10.8	0.15	5.7
	Bo1	4.6	5.1	-0.5	52.4	0.8	6.1	1.3	0.6	0.2	4.9	2.0	2.2	7.0	29.2	8.1	1.5	9.8	0.1	36.0	3.6	1.5	0.14	49.5
	Bo2	4.8	5.4	-0.6	21.7	0.7	8.2	1.3	0.9	0.1	4.2	2.2	2.3	6.5	34.5	4.3	1.2	9.5	0.1	20.7	3.0	1.3	0.10	52.8
HAPLUDULT (AND)	Ap	6.7	7.5	-0.9	188.7	158.8	32.0	7.8	1.7	0.0	1.3	9.9	10.0	11.2	88.3	0.3	2.6	35.2	13.6	39.0	110.8	6.4	0.31	6.2
	Bt1	4.3	4.9	-0.6	60.3	0.9	6.1	1.3	0.5	0.4	3.9	2.0	2.4	5.9	33.5	16.6	0.6	11.0	0.2	50.5	3.7	2.5	0.08	44.4
	Bt2	4.8	5.1	-0.3	56.3	0.9	7.2	0.9	0.4	0.1	2.9	1.4	1.5	4.3	32.1	9.2	0.4	6.2	0.2	34.2	4.3	2.1	0.08	48.4
HAPLUDULT (PIN)	A	6.1	6.8	-0.7	165.0	4.0	5.1	3.6	1.7	0.1	1.6	5.7	5.8	7.3	77.8	0.9	2.1	33.2	2.1	174.6	16.2	1.8	0.15	4.0
	Bt1	4.2	4.6	-0.4	22.7	0.8	4.1	0.6	0.4	0.7	3.9	1.0	1.7	4.9	20.5	41.3	0.9	25.1	0.1	87.2	1.6	0.7	0.06	36.6
	Bt2	4.2	4.5	-0.3	38.5	0.9	6.1	0.5	0.4	0.7	3.8	1.1	1.7	4.8	21.9	39.1	0.7	15.7	0.1	24.9	1.3	0.7	0.08	45.9
	BC	4.7	4.8	-0.1	49.4	0.5	11.3	0.4	0.3	0.1	2.1	0.9	1.0	3.0	29.4	8.4	0.3	14.2	0.1	15.4	2.8	0.3	0.07	44.9
EUTRUDEPT (ITO)	A	5.0	6.2	-1.2	168.0	156.3	11.3	3.7	1.2	0.0	3.3	5.3	5.4	8.6	62.0	0.7	1.5	39.6	10.2	43.8	30.2	3.5	0.20	3.3
	Bw	5.6	6.4	-0.8	69.2	1.8	11.3	2.6	0.8	0.0	1.7	3.6	3.6	5.3	67.3	0.8	0.4	18.8	1.3	50.7	13.9	0.6	0.08	15.7
ACRUDOX (SSP)	Ap	4.5	5.6	-1.2	126.5	20.9	6.1	1.5	0.4	0.2	4.5	2.2	2.4	6.7	32.8	7.6	2.3	26.5	9.9	38.9	20.7	7.2	0.10	15.4
	Bo1	6.6	7.4	-0.9	43.5	0.3	5.1	1.6	0.5	0.0	1.6	2.2	2.2	3.7	57.8	0.9	1.4	6.6	0.1	53.1	10.4	5.7	0.08	13.5
	Bo2	6.3	6.7	-0.4	27.7	0.1	5.1	1.1	0.4	0.0	1.7	1.6	1.6	3.3	48.7	2.5	1.0	4.4	0.1	54.0	7.5	5.2	0.06	42.2
HAPLUDOX (TP)	Ap	5.9	6.5	-0.6	288.5	540.2	21.7	5.3	1.1	0.0	2.3	7.1	7.2	9.5	75.5	0.6	2.3	35.9	17.1	35.2	23.8	6.1	0.29	9.4
	Bo1	4.7	5.0	-0.3	140.3	0.4	8.2	1.1	0.3	0.2	3.2	1.7	1.9	4.9	35.3	8.0	1.4	11.1	0.1	26.5	2.9	1.4	0.21	51.7
	Bo2	5.9	6.1	-0.2	115.6	0.1	10.3	1.3	0.2	0.0	1.8	1.8	1.8	3.7	49.5	1.6	0.6	3.0	0.1	25.2	3.3	1.4	0.23	50.8

Hz - soil horizon; SB: sum of bases; ECEC - effective cation exchange capacity; CEC - cation exchange capacity at pH 7.0; BS - base saturation; AS - aluminum saturation; SOM - soil organic matter; Rem-P - remaining phosphorus.

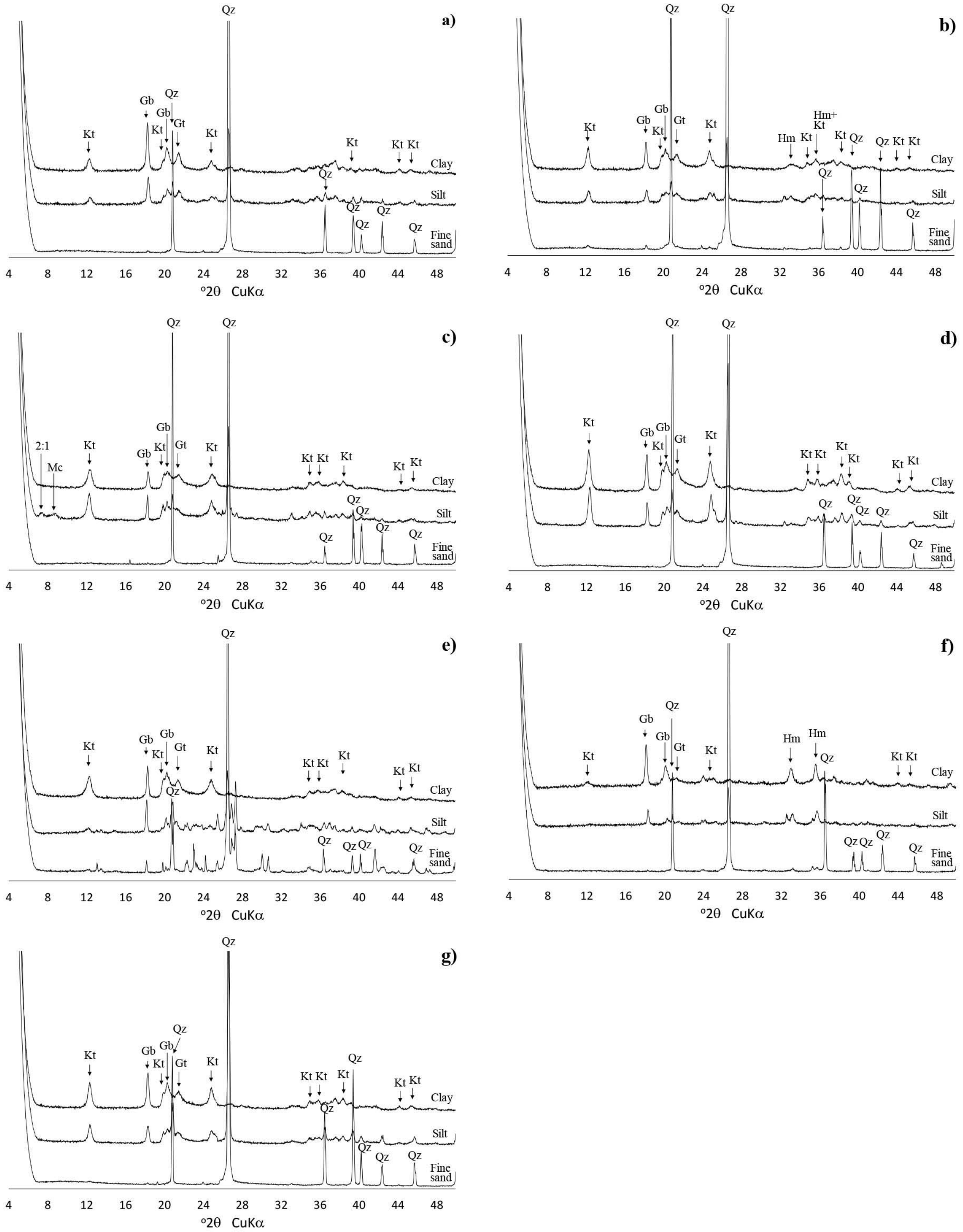

FIGURE 3. Mineralogical composition of the soil B horizon. a) TC-Acrudox; b) COR – Acrudox; c) AND – Hapludult; d) PIN – Hapludult; e) ITO – Eutrudept; f) SSP – Acrudox; g) TP – Hapludox. Kt: kaolinite; Gb: gibbsite; Gt: goethite; Hm: hematite; Mh: maghemite; Qz: quartz; Ot: orthoclase; Mc: mica.

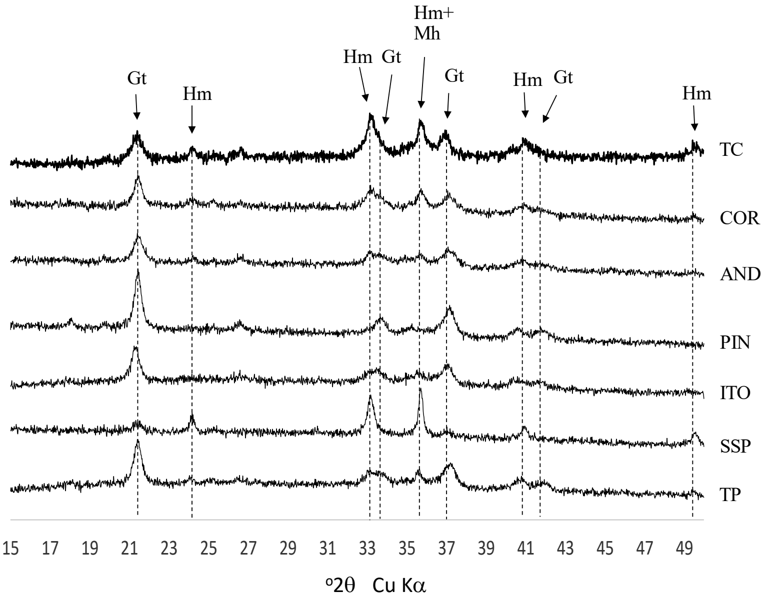

FIGURE 4. X-ray diffractograms of iron oxides of clay fraction from soil B horizons. TC – Acrudox; COR – Acrudox; AND – Hapludult; PIN – Hapludult; ITO – Eutrudept; SSP – Acrudox; TP – Hapludox. Gt: goethite; Hm: Hematite; Mh: Maghemite.

parent material analyses, alongside the pXRF spectrometry, revealed soils which had different tracer characteristics formed from the same parent material (Resende *et al.*, 2019; Silva *et al.*, 2019); this might be due to differential pedogenetic processes promoting soil differentiation. Regarding terroir, Maltman (2008) reported the occurrence of vineyards in different regions being located on similar bedrock, with the soils producing a high variety of wine styles. Therefore, pXRF spectroscopy has high potential for assisting terroir characterisation on a local scale.

5. Climatic characterisation

Temperature and rainfall did not negatively impact the winegrowing activities in the regions studied. The accumulated rainfall during the maturation period of vineyards ranged from 72 to 115 mm (Figure 6a). The COR, AND and PIN vineyards had the highest accumulated volume during the period considered. Low rainfall during the ripening period is positive in that it leads to the accumulation of sugars and phenolic compounds in grapes (Amorim *et al.*, 2005).

Thermal amplitude ranged from 12.6 to 15.4 °C, with the highest values for TC, COR and TP (Figure 6b). The AND, PIN and SSP vineyards had the mildest atmospheric temperatures, with the maximum below 24 °C. ITO showed a warm climate from May to July, with the highest maximum and minimum temperatures. It is important to highlight that such high thermal amplitudes favour the accumulation of phenolic compounds, which are directly related to wine composition and quality (Conde *et al.*, 2007). Up to certain limits, higher temperatures during the maturation period can result in an increase in the pH of wines (Brant *et al.*, 2021; Conde *et al.*, 2007), making them more susceptible to oxidation and damage caused by microorganisms (van Leeuwen *et al.*, 2018).

6. Principal component analysis and relationships between soil, climate and wine characteristics

As the different combinations of physical, chemical and mineralogical soil properties and climate characteristics affect the quality of wines in different ways, a PCA analysis was carried out to group the vineyards according to soil and environmental similarities. The PCA analysis was performed separately on information from the A and B horizons (Figure 7 and 8 respectively) in order to best characterise the soil-environment scenarios. As expected, the same attributes showed different vector sizes in the A and B horizons (the greater the distance from the PCA origin, the better the representation). In addition, AWC and sand content were found to be positively correlated in both soil horizons; although the soils are mostly clayey, ITO and PIN are relatively sandier and thus had higher AWC values. In addition, the analysis of the proximity of vineyards in PCA showed that they are grouped differently in terms of A and B horizons. There may be several reasons for such contrasts: a) soil chemical-physical characteristics differ considerably with depth due to human factors (application of soil amendments) and environmental factors (pedogenetic processes causing differentiation in soil structure, SOM, clay accumulation in depth and other aspects), b) most of the fine roots are found in the first 60 cm of depth, reaching the A and B horizons (Smart *et al.*, 2006), c) soil classification is an important source of information and, considering the soil types found, information about the subsurface horizons govern the classification at the first

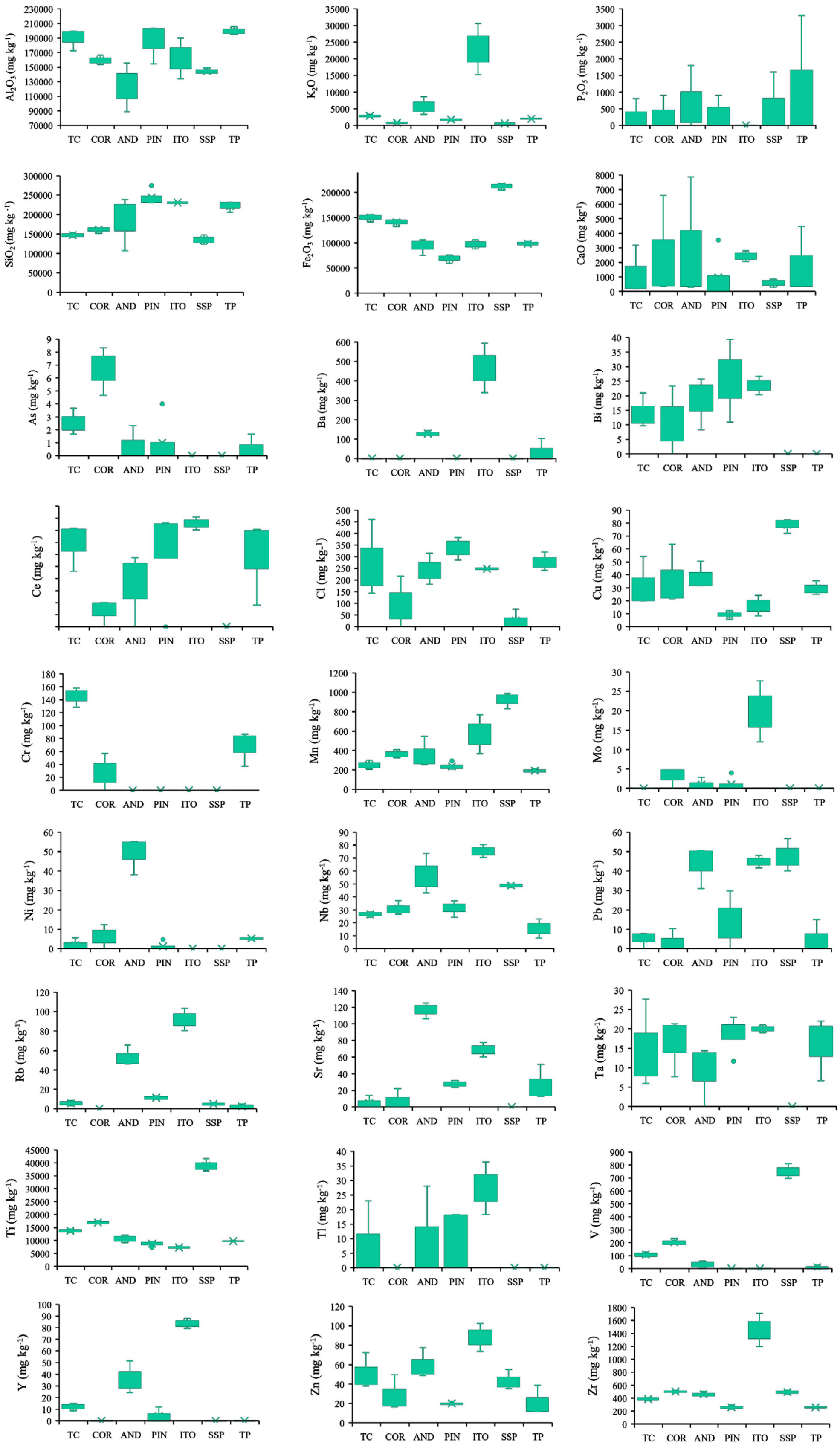

FIGURE 5. Boxplots comparing elemental and oxide content determined via portable X-ray fluorescence (pXRF) spectrometry in soils of vineyards in southeastern Brazil. TC-Acrudox; COR – Acrudox; AND – Hapludult; PIN – Hapludult; ITO – Eutrudept; SSP – Acrudox; TP – Hapludox.

TABLE 3. Fe content extracted with dithionite (Fe_d) and oxalate (Fe_o) in the clay fraction.

Horizon	Fed ($g\ kg^{-1}$)	Feo ($g\ kg^{-1}$)	Fe_o/Fe_d
ACRUDOX (TC)			
Ap	125.8	1.3	0.01
Bo1	101.8	1.1	0.01
Bo2	109.8	1.0	0.01
ACRUDOX (COR)			
Ap	113.8	2.7	0.02
Bo1	120.5	2.6	0.02
Bo2	121.4	3.1	0.03
HAPLUDULT (AND)			
Ap	84.8	4.1	0.05
Bt1	96.0	2.6	0.03
Bt2	95.3	2.5	0.03
HAPLUDULT (PIN)			
Ap	70.2	2.6	0.04
Bt1	62.3	0.9	0.01
Bt2	54.1	0.8	0.01
BC	77.2	1.0	0.01
EUTRUDEPT (ITO)			
Ap	82.6	3.1	0.04
Bw	106.4	1.5	0.01
ACRUDOX (SSP)			
Ap	273.1	4.0	0.01
Bo1	238.6	3.8	0.02
Bo2	242.4	3.7	0.02
HAPLUDOX (TP)			
Ap	78.2	2.1	0.03
Bo1	77.6	1.3	0.02
Bo2	76.3	1.0	0.01

categorical level (order) (Soil Survey Staff, 2014), and d) soil air is different from atmospheric air.

Even under the same atmospheric conditions, different soils behave differently depending on their characteristics, such as SOM, water availability and storage, coarse fragment content (governing soil temperature variations), shape of structure, texture, electric charges and depth (governing water movement). Thus, different relations and interactions were found involving soil × climate in the PCA analysis of each soil horizon. The vineyards were characterised based on the groups formed by PCA with data from the B horizon in order to facilitate understanding, taking into account that the

B horizon governs soil classification at the first categorical level (order) (Soil Survey Staff, 2014), and that this subsurface horizon dries out much later than the surface horizon (a very important condition for perennial crops, such as vineyards). As expected, highly correlated variables were mainly found related to soil and some wine composition analysis. Thus, the following discussion focuses mostly on the grouping of vineyards (the closer the vineyards in the biplot, the greater their similarity in terms of group formation) and the most correlated variables of each specific group in terms of soil, climate and wine composition. In addition, the A-horizon characteristics are discussed together to take all the soil profile information into account.

Both the climatic and soil characteristics were important for grouping the vineyards (groups formed are discussed further). The definition of the groups was based on the proximity of the vineyard data in the plots (Figures 7 and 8). The groups formed according to soil-environment characteristics showed high differentiation in terms of wine composition (Figure 9), on which wine typicity is based.

Group A) Comprising the COR, AND and PIN vineyards. The soil characteristics of the A horizons were quite different (Figure 7), mainly due to differences in management

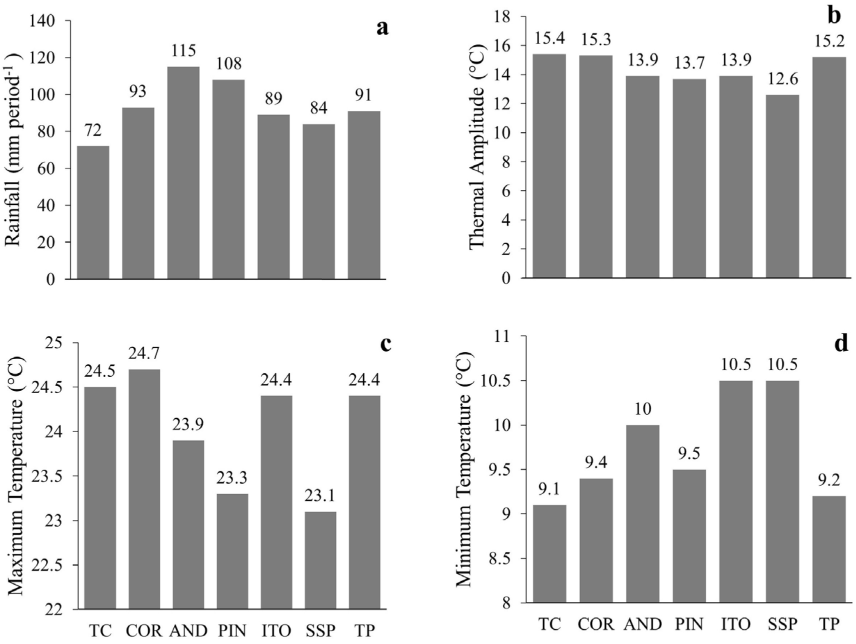

FIGURE 6. Climatic characteristics of the vineyards during the maturation period (May to July). AND: Andradas; COR: Cordislândia; ITO: Itobí; PIN: Espírito Santo do Pinhal; SSP: São Sebastião do Paraíso; TC: Três Corações; TP: Três Pontas.

practices. The B horizon showed greater correlation with elements related to Al^{3+} and AS, with the highest values being observed in PIN. The climatic variable most related to this group was accumulated rainfall, for which the highest values were obtained (Figure 7). Figure 9 shows that the wines produced in this group had the lowest values for ash alkalinity and total polyphenols index (TPI). In addition, the group's wines had the lowest pH and the highest fixed acidity.

Group B) Comprising the TP and TC vineyards. The PCA results showed that high levels of SOM and boron in the soil subsurface are common to these vineyards. According to Brant *et al.* (2021), higher SOM content may have ensured greater vine yield in this region. Another similarity in the soils of this group is the clay texture throughout the soil profile. These vineyards have similar higher thermal amplitude (15.4 °C in TC and 15.2 °C in TP) (Figure 6b). Most wine composition parameters showed high variation and more intermediate values compared to the other groups. The most similar parameters for TC and TP (respectively in brackets) were alcohol (13.85 and 14.20 %), TPI (58.14 and 57.56), and sugars (2.94 and 3.31 g L^{-1}). TC and TP wines had a fixed acidity of 6.07 g L^{-1} and 5.04 g L^{-1} respectively, whereas their pH was 3.73 and 4.17 respectively. The lower acidity of TP wine is associated with high soil K content (van Leeuwen *et al.*, 2018), since K tends to decrease the concentration of free acids in wines. Colour intensity is also lower in soils with high contents of this nutrient, as was found in TP (Davies *et al*., 2006).

Group C) Comprising the ITO vineyard. The PCA results clearly differentiated this vineyard soil from the other vineyards, the most notable differences in morphological attributes being the reduced thickness of the soil and the more limited pedogenetic development. This soil was found to have high subsurface sand content (correlated with AWC) and the highest effective CEC, as well as Ca^{2+}, Mg^{2+} and total K_2O content, as determined by the pXRF. In contrast to the other soils, altered granite was recorded as the parent material at a depth of 70 cm. The wine from this vineyard had the highest flavanol content. High values for dry extract, colour intensity, TPI, alcohol content and sugars were also found (Figure 9). The high wine pH might be due to the high average atmospheric temperatures during the maturation period, which favour the degradation of malic acid (Brant *et al.*, 2021; Conde *et al.*, 2007). The high residual sugar content may have been caused not only by the high temperatures, but also by the low precipitation (Amorim *et al.*, 2005) and the low soil water retention (van Leeuwen *et al.*, 2009) and storage; in addition, high alcohol content inhibits the activity of yeasts, leaving a high residual sugar content. Similar to this vineyard, grapes with high oenological potential have shown high TPI in less weathered soils in France (Morlat and Bodin, 2006).

Group D) Comprising the SSP vineyard. Although this vineyard contains Acrudox soil, which was also found in the other vineyards, it has very different parent material (mixture of basalt and sandstone). The subsurface horizons of this soil revealed high water pH. The late harvest in this vineyard caused greater dehydration of grapes and the consequent concentration of most of the wine compounds (Brant *et al.*, 2021), making it difficult to determine the

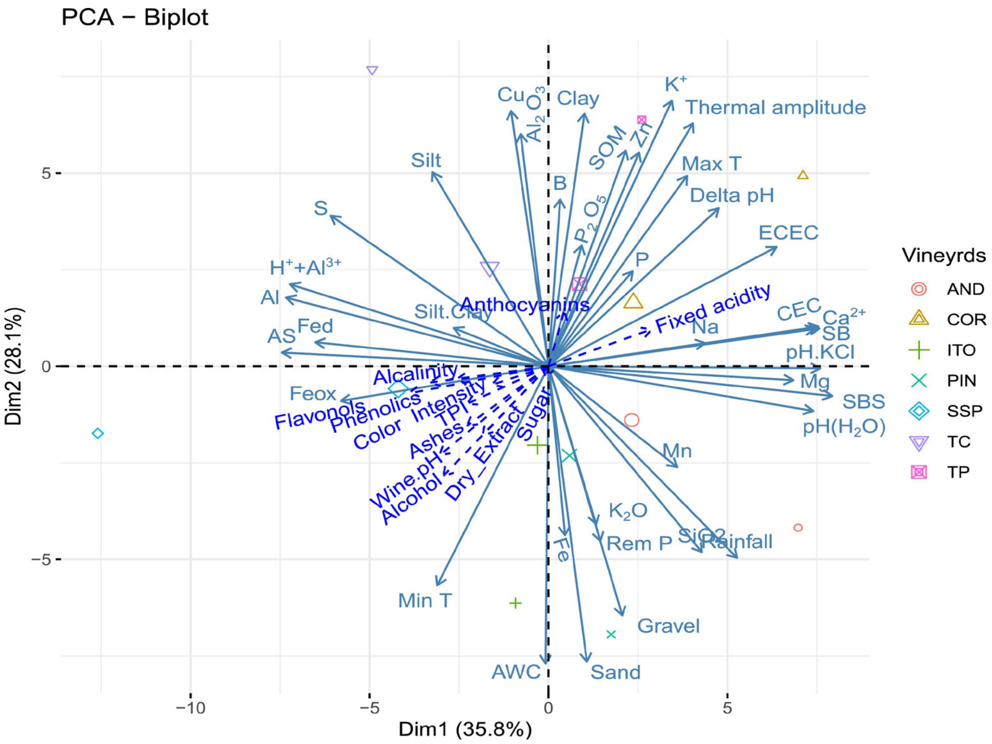

FIGURE 7. Biplot of first principal component (Dim1) and second principal component (Dim 2). A-horizon data and climatic data as active variables and wine composition as a supplementary variable. AND: Andradas; COR: Cordislândia; ITO: Itobí; PIN: Espírito Santo do Pinhal; SSP: São Sebastião do Paraíso; TC: Três Corações; TP: Três Pontas.

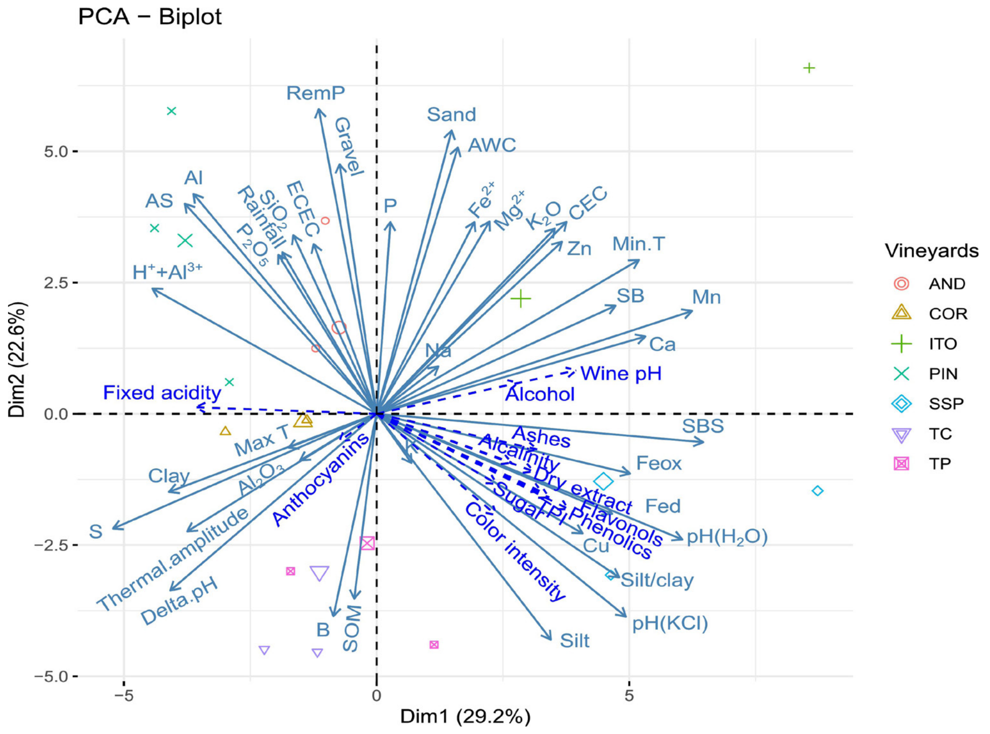

FIGURE 8. Biplot of first principal component (Dim1) and second principal component (Dim 2). B-horizon data and climatic data as active variables, and wine composition as a supplementary variable. AND: Andradas; COR: Cordislândia; ITO: Itobí; PIN: Espírito Santo do Pinhal; SSP: São Sebastião do Paraíso; TC: Três Corações; TP: Três Pontas.

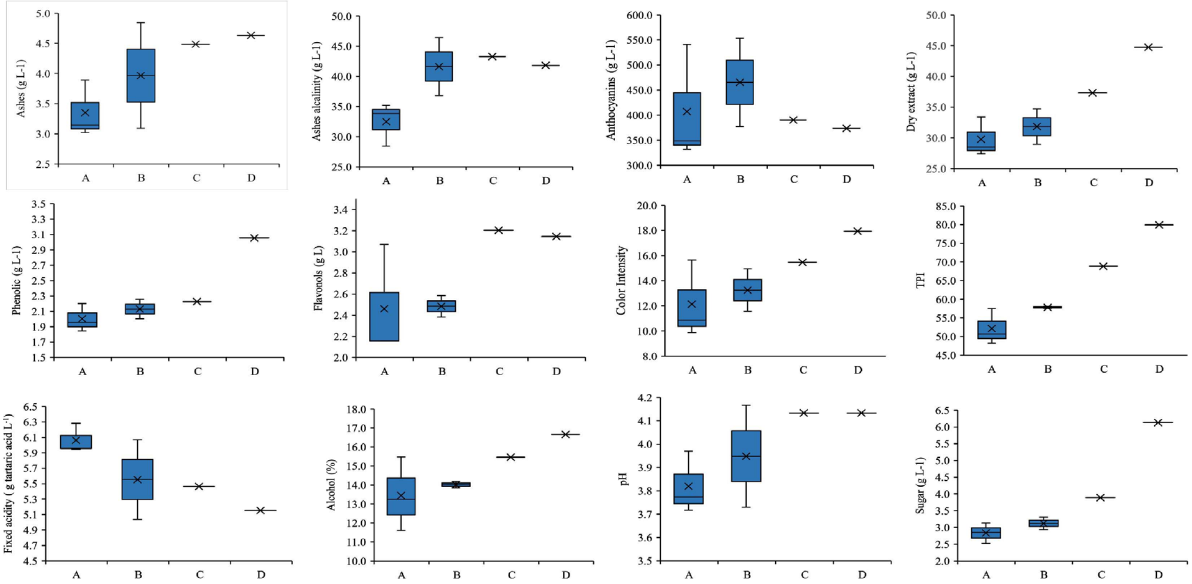

FIGURE 9. Boxplots showing the composition of winter wines according to soil group and to clustering by PCA with B-horizon attributes. A) Cordislândia (COR), Andradas (AND), and Espírito Santo do Pinhal (PIN); B) Três Corações (TC) and Três Pontas (TP); C) Itobí (ITO); D) São Sebastião do Paraíso (SSP).

correlation between the wine compounds and soil and climatic attributes related to this vineyard (Figures 7 and 8).

In all the studied environments, the winter wine composition (which determines wine quality) was within the range of the composition of wines produced in different renown viticultural regions around the world; e.g., the alcohol content and pH values were similar to those found in California (Brillante *et al.*, 2018); the alcohol content, anthocyanin and TPI values were similar to those in wines from Greece (Koundouras *et al.*, 2006) and the anthocyanin values (Ristic *et al.*, 2007), alcohol content and pH values were similar to those determined in wines from Italy (Priori *et al.*, 2019).

CONCLUSIONS

Soil and climate attributes affected wine composition. The parent material of the vineyard soils was found to be quite diverse: the parent material of the AND and TP vineyards is gneiss and that of PIN and ITO granite. In these cases, the different degrees of weathering of the parent material resulted in morphological, physical, chemical and mineralogical differences among the soils. The ITO vineyard has a shallower soil, with low water storage capacity; it also has the highest atmospheric temperature, which promotes synthesis of anthocyanins, flavanols, TPI and alcohol. The soil and climate conditions of this vineyard were the most diverse in this study, which allowed the effect of environment on the composition of the wines to be clearly visualised. A similar tendency was found for the group comprising the COR, AND and PIN vineyards, which have soil water conditions that lead to the production of wines with a low pH. The terroir information produced here substantially increases the added value of the wines produced in the tropical environmental conditions of southeastern Brazil, where such studies are quite rare. By characterising natural factors (soil, soil parent material and climate) and human factors (vineyards management and wine characteristics), this study can also contribute to the third terroir factor, which consists of the knowledge of the wine from this emergent region (historical factors). In addition, its results can help guide producers in choosing vineyard cultivation sites according to preference in wine composition.

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