Impact of intra-vineyard soil heterogeneity on Malbec. Vine growth, yield and wine elemental composition and sensory profile

Impacto de la heterogeneidad de suelo intra parcelaria en Malbec. Crecimiento, rendimiento, composición elemental y perfil sensorial de sus vinos

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Abstract

In Mendoza, viticulture is increasingly expanding into mountainous regions, taking advantage of cooler temperatures. High-altitude vineyards, characterized by greater soil heterogeneity, can significantly impact grapevine growth, development, elemental uptake, and wine sensory attributes. Despite its relevance, the effects of intra-vineyard variability on wine organoleptic quality and elemental composition remain underexplored in the existing literature. This study investigated a high-altitude vineyard planted with *Vitis vinifera* L. cv. “Malbec”, focusing on two contrasting soil depth profiles: shallow soil (SS) and deep soil (DS). The DS exhibited a finer texture, higher water retention and greater cation exchange capacity than the SS. Additionally, DS contained higher concentrations of Mn, while SS was richer in Ca. Vegetative growth and yield varied according to soil type and vintage. Wines from DS showed higher [Mn], consistent with the soil, and increased [Fe] and [Cu] compared to SS wines, possibly due to indirect effects. Significant differences were observed in wine organoleptic properties, with SS wines exhibiting greater color intensity, astringency, and structure. Certain aromas, such as cherry and plum were negatively correlated with [Mn]. These findings highlight the influence of vineyard soils on the elemental composition and sensory profiles of wines, providing valuable insights into terroir characteristics for management strategies.

Keywords
cationic profile • edaphic variability • organoleptic wine properties • phenotypic expression • soil type • terroir

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Resumen

En Mendoza, la viticultura está en expansión creciente hacia áreas montañosas para aprovechar temperaturas más frescas. Los viñedos de altura, que están caracterizados por una mayor heterogeneidad del suelo, pueden influir significativamente en el crecimiento, desarrollo, absorción de elementos, y atributos sensoriales de las uvas y vinos. A pesar de su relevancia, los impactos de la variabilidad a nivel intra parcelario, en la calidad organoléptica y la composición elemental de los vinos, han sido poco explorados en la literatura existente. Este estudio investigó un viñedo de altura plantado con *Vitis vinifera* L. cv. "Malbec", centrándose en dos sectores con profundidad contrastante de suelo: suelo superficial (SS) y suelo profundo (DS). DS presentó una textura más fina, mayor capacidad de retención de agua y mayor capacidad de intercambio catiónico en comparación con SS. Además, DS mostró mayores concentraciones de Mn, mientras que SS tuvo más [Ca]. El crecimiento vegetativo y el rendimiento variaron según el tipo de suelo y la temporada de cultivo. Los vinos de DS presentaron mayor [Mn] en concordancia con el suelo y mayor [Fe] y [Cu] en comparación con los vinos de SS, posiblemente debido a efectos indirectos. Se encontraron diferencias significativas en las propiedades organolépticas de los vinos, con una mayor intensidad de color, astringencia y estructura en los vinos de SS. Algunos aromas, como cereza o ciruela, se correlacionaron negativamente con [Mn]. Estos hallazgos destacan la influencia de los suelos del viñedo en la composición elemental y los perfiles sensoriales del vino, contribuyendo a la comprensión de las características del terroir para estrategias de manejo.

Palabras clave
perfil catiónico • variabilidad edáfica • propiedades organolépticas del vino • expresión fenotípica • tipo de suelo • terruño

Introduction

In Mendoza, Argentina's primary wine-growing region, vineyards planted near the Andes mountain in the Uco Valley, at altitudes ranging from 900 to 1,500 m above sea level, have expanded rapidly in recent years. Malbec is the most widely planted red grapevine cultivar in Argentina, covering 42,999 ha, with 85.1% of this area located in Mendoza province (30). According to the literature, high-altitude vineyards are generally defined as those located within a broad elevation range of 350 m to 2,900 m a. s. l. (46), with the primary goal of achieving optimal temperatures for grapevine cultivation. As a result, high-altitude viticulture is gaining significance due to its potential to produce high-quality wines in regions increasingly affected by global warming (3).

As vineyards are planted closer to the mountains in search of optimal temperatures, they also experience other environmental changes, such as fluctuations in ambient humidity, wind patterns, and increased exposure to ultraviolet-B radiation (UV-B) (3, 8). Soil composition constitutes one critical factor to be considered in mountainous environments (21). Soils play a fundamental role in balancing the vegetative and reproductive development of grapevines, influencing berry quality and the sensory profile of the resulting wine (56). In foothill areas, soils are shaped by alluvial and fluvial processes, forming alluvial cones with variations in soil depth, texture, and rock volume, which lead to pronounced soil heterogeneity at an intra-vineyard scale (≤ 1 ha) (21, 41, 50). This- high degree of variability can significantly affect grapevine cultivation and wine quality (11). Differences in soil depth can result in physical and chemical variations, such as changes in texture, water-holding capacity, and cation exchange capacity (CEC) (50), all of which impact root development, water uptake and nutrient absorption (60). These factors, in turn, influence vegetative growth, yield, and the quality and sensory profile of berries and wines (61). Considering Malbec cultivar, Roig-Puscama *et al.* (2021) reported that strong soil heterogeneity within a single vineyard induces changes in the xylem structure of grapevine main stems, interpreted as an adaptive response to differences in soil water retention capacity. Soils with low water retention can induce water stress, leading to higher levels of abscisic acid (ABA) and, consequently, increased total polyphenol content in berries and wines under heterogeneous soil conditions (47). This variability can produce wines with distinct styles from the same vineyard (11). Intra-vineyard variability challenges viticulturists and winemakers who seek uniform fruit parcels for specific products (12). However, it also offers an opportunity for winemakers to differentiate their products by leveraging the unique characteristics of soil heterogeneity.

Soil heterogeneity influences mineral composition, affecting uptake and accumulation of elements in grapevines. Regional-scale studies have demonstrated a correlation between the elemental composition of soils, berries and wines, facilitating the identification of a wine's geographical origin (32, 39). Berry and wine elemental profile primarily reflects soil characteristics, shaped by its distinct geological features (2). However, the accumulation of these elements can vary depending on the plant material (31), while changes in soil fertility may influence the ripening process and sugar accumulation in berries (29). Variations in elemental content in berries can also affect oxidation-reduction reactions during vinification, leading to differences in organoleptic properties and, ultimately, wine quality (55). Despite this, the relationship between soil elemental composition and sensory attributes of wine remains poorly understood (36).

Previous studies on the effects of soil in vineyards have primarily been conducted at a regional scale, making it difficult to disentangle key influencing factors such as climate and topography (25, 32, 59). Moreover, there is limited understanding of how soil elemental concentrations at the intra-vineyard scale affect the elemental composition of wine and, consequently, its organoleptic characteristics.

This study aimed to examine the influence of two soil types with contrasting properties, specifically depth, texture, and the presence of boulders, on vegetative growth, yield, elemental composition, and the sensory profile of wines at an intra-vineyard scale. Importantly, the objective was not to propose management strategies for homogenizing vigor and yield based on soil type. Instead, the analysis was conducted within a high-altitude Malbec vineyard, where plant material, management practices, and climate were controlled as fixed factors.

Material and methods

Study site

The study was conducted over three growing seasons (2017-2019) in a high-altitude commercial vineyard located within the Geographical Indication (GI) "Paraje Altamira" (Zuccardi Valle de Uco winery, 33°46'20.29'' S; 69°9'14.62'' W; 1,100 m a. s. l.), Mendoza, Argentina. This vineyard, situated in the foothills of the Andes mountains, is characterized by significant soil heterogeneity.

Plant material and vineyard characteristics

The study focused on a 2.5-ha parcel planted in 2009 with own-rooted *Vitis vinifera* cv. Malbec, derived from massal selection. The vines were 8 years old at the start of the study. The vineyard was trained using the Double Guyot system, with each vine pruned to two five-bud canes (long fruit-bearing shoots) and two-bud spurs (short shoots for renewal), totaling 14 buds per plants. Rows were oriented north-south, with a planting density of 1.8 m between rows and 0.8 m between plants. Shoots were vertically positioned using foliage wires, and the vineyard was equipped with anti-hail nets and drip irrigation. Fertigation consisted of potassium (potassium nitrate), nitrogen (urea) and phosphoric acid, applied at a rate of 25-7-12 N-P-K units over five weeks between flowering and fruit set. Pathogen management included micronized sulfur (7.2 kg ha^{-1} in four applications per season), and three $CuSO_4$ applications per season, with increasing concentration of 1% for the first two applications and 1.5% for the third. All management practices were applied uniformly across soil types.

Experimental design

Sectors with contrasting soil depths were identified using electromagnetic conductivity (EMC) maps generated with an EM38MK2 ground meter (Geonics Ltd., Canada). Measurements were taken at depths of 0.75 m and 1.5 m, identifying six conductivity classes ranging from 1.06 to 5.24 mS m^{-1}. The two extreme classes were selected using GIS software (48), and soil properties were confirmed through trench excavations. Two distinct soil types were identified. Shallow soils (SS) contained boulders (>0.3 m in diameter) occupying ~85% of the soil profile, with an alluvial layer depth of 0.2-0.3 m. Deep soils (DS) consisted of alluvial sediments with a sandy-loam texture and an average depth of 2 m. The depth and structure of both soil types are shown in figure 1. Six experimental units (plots) were established per soil type, totaling 12 plots. Each plot covered 184 m^2 and included 128 plants (figure 1).

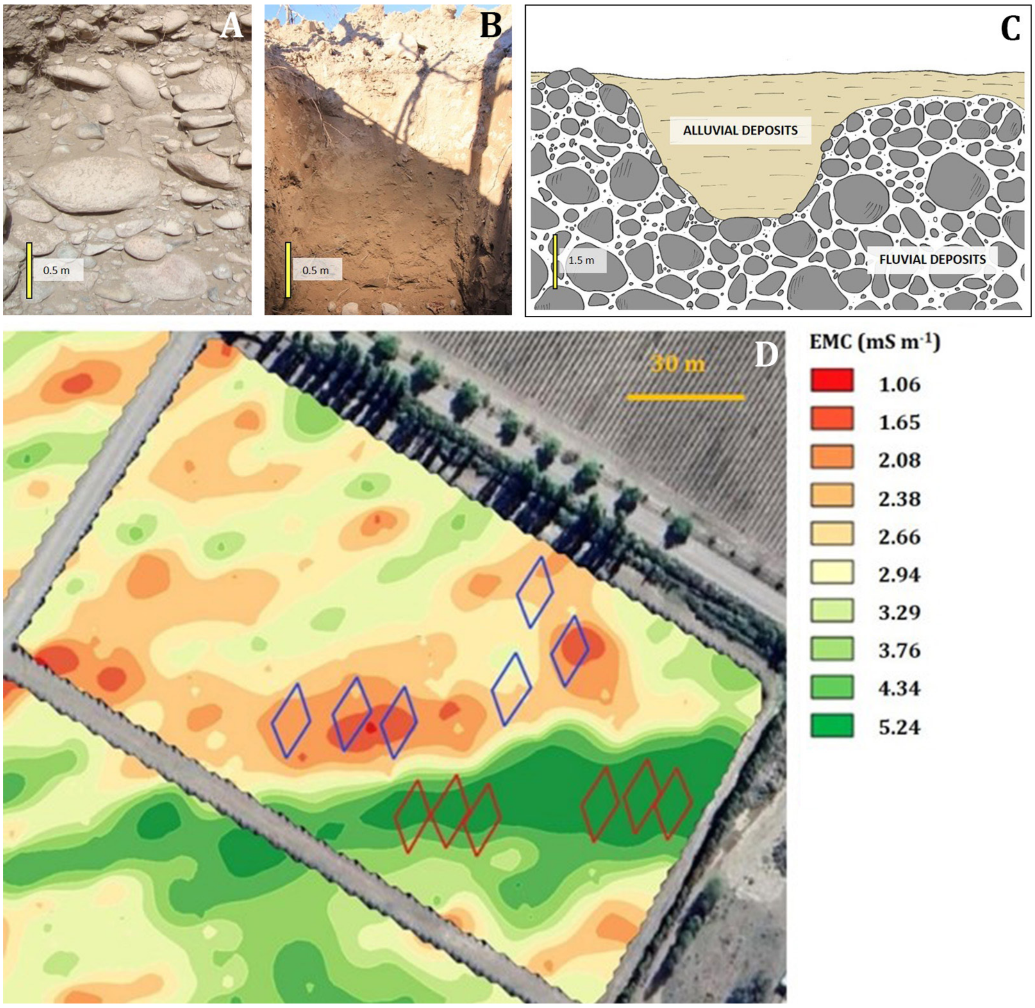


Figure 1. Vertical profile of soil structure and depth for SS (A) and DS (B). Schematic representation of soil profile found in Paraje Altamira (C). Electromagnetic conductivity (EMC) maps measured with the EM38 MK2 ground meter and EMC values. Experimental blocks are showed with parallelogram: reds for SS and blues for DS (D).

Figura 1. Perfil vertical de la estructura y profundidad del suelo para SS (A) y DS (B). Representación esquemática del perfil de suelo encontrado en Paraje Altamira (C). Mapas de conductividad electromagnética (EMC) medidos con el medidor de suelo EM38 MK2 y los valores de EMC. Los bloques experimentales se muestran con un paralelogramo: rojos para SS y azules para DS (D).

Soil sampling and analysis

Soil sampling was conducted in 2017 at the start of the study during trench excavations used to define soil types. Composite soil samples were collected from each plot at a depth of 0.20-1 m to minimize surface contaminants and capture the root zone. Soil texture was analyzed using the hydrometer method described by Bouyoucos (1951) and cation exchange capacity (CEC) was determined following Richards (1954). Water-holding capacity, including saturated water point (Ws), field capacity (Wc) and permanent wilting point (Wp), was estimated using pedotransfer functions based on soil texture classes (14, 49). Elemental composition was determined by acid digestion following Funes-Pinter (2018) Dried soil samples were treated with a mixture of HNO_3 (65%), HCl (37%), HCl_4 (65%), and H_2O_2 (30% vol), followed by centrifugation and dilution. Elemental analysis was performed using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) with a PerkinElmer SCIEX, ELAN DRC-e equipment (Thornhill, Canada), to quantify Mg, Ca, Na, K, Mn, Fe, Cu, Al, Zn, Li, Rb, and Cd concentrations.

Vegetative growth, yield components

Vegetative growth and yield observations were assessed annually over three growing seasons (2017-2019). Three healthy and homogeneous plants per plot were randomly selected for monitoring. During the growing season, at the berry pea-size phenological stage (fruit diameter ~5 mm, classified by Baggiolini (1952), measurements were taken for shoot length, internode length, and shoot diameter, key indicators of vine vigor. For this purpose, the north-directed cane in the row was selected on each plant, corresponding to the five-bud canes left during pruning, as described in the vineyard characteristics section. Shoot diameter was measured with a caliper at the midpoint of the first internode, and average values were recorded for each plant. At harvest, yield components were evaluated, including the number of bunches per plant, bunch weight, yield per plant, berries per bunch, and berry weight. During winter dormancy, vegetative growth was further assessed by measuring total pruning weight per plant, another key vigor indicator. These measurements were performed on the same plants monitored during the growing season. The yield to pruning weight ratio was expressed as the Ravaz index (27). Additionally, stem water potential (Ψ_{stem}) was measured weekly from flowering to mid-veraison each season using a Scholander pressure chamber, following Scholander (1965). Fully expanded leaves were covered with aluminum foil at least one hour before measurement to ensure equilibration, and Ψ_{stem} values were recorded to assess plant water status.

Harvest and vinification procedure

Harvesting was conducted at commercial maturity, defined at a sugar concentration of 24 °Brix (1° Brix = 1 g of sugar per 100 mL of grape juice). Harvest dates varied by soil type (table S1). All plants in each plot were harvested, and grapes were collected in 16 kg boxes to minimize berry breakage. Quality control at the winery involved discarding dehydrated grapes and those showing signs of Botrytis infection. Micro-vinifications were performed for each plot following the standardized protocols of Zuccardi Valle de Uco Winery. Grapes were destemmed, sulphited, and placed in 50 kg stainless steel tanks, then inoculated with a proprietary yeast poll (confidential data). Maceration and alcoholic fermentation occurred over 12 days at 25-28°C. Wines were then transferred to 20 L plastic tanks for malolactic fermentation, with pH adjusted to 3.75 using tartaric acid and free sulfur dioxide corrected to 45 mg L^{-1}. Finally, wines were bottled in 0.75 L glass bottles and stored at 20°C in darkness until analysis.

Elemental composition of wines and descriptive sensory analysis

The elemental composition of wine samples was analyzed using ICP-MS, following a modified version of the soil analysis protocol. Five milliliters of each wine sample were transferred into a 15 mL tube, and 0.5 mL of 65% HNO_3 was added. The mixture was vortexed for 15 seconds, microwaved for 15 seconds at 600 W, and diluted with 9.5 mL of ultrapure water. Subsequently, 1 mL of the diluted sample was mixed with 1 mL of 65% HNO_3, sonicated for 30 minutes, and combined with 0.5 mL of H_2O_2. The mixture was heated in a water bath at 60°C for 60 minutes, then diluted with 9.5 mL of ultrapure water, and used for elemental analysis.

Additionally, wines from each plot were evaluated through quantitative descriptive sensory analysis (QDA), following the protocol described by Lawless and Heymann (2010). Two bottles of wine from each plot were analyzed. A professional panel of eight tasters from Argentina's National Institute of Viticulture (INV) established sensory descriptors for each soil type, covering visual, aroma, and taste attributes. These included 11 aroma descriptors, 11 taste descriptors, and 5 visual descriptors (table 1).

Sensory evaluations were conducted in individual booths. Each panelist used a structured tasting sheet with an unstructured scale from 1 (very low intensity) to 5 (very high intensity). Wine samples (30 mL) were served at room temperature in ISO-standard tasting glasses (ISO 3591-1977), covered with plastic lids and coded for blind evaluation.

Table 1. General sensory descriptors in Malbec wines from both types of soil during tasting consensus.

Tabla 1. Descriptores sensoriales generales encontrados en los vinos Malbec de ambos tipos de suelo durante el consenso realizado por el panel de cata.

Visual	Aroma		Taste/Mouthfeel	
Clarity	Mineral note	Caramel sauce	Acid	Unctuous
Color intensity	Strawberry	Peppers	Sweet	
Red Hue	Plum	Vanilla	Astringent	
Violet hue	Cherry	Chocolate	Hot	
Garnet hue	Blackberry	Jam/Liqueur	Bitter	
	Violets	Global intensity	Structure	

Statistical analysis

Soil physicochemical variables and elemental composition data were analyzed using non-parametric tests($p \leq 0.05$, Kruskall-Wallis), as the data did not meet the normality and homoscedasticity assumptions required for parametric tests. Vegetative growth and yield components were analyzed by multifactorial ANOVA (soil type and growing seasons; Fisher's LSD, $p \leq 0.05$). All statistical analyses were performed using InfoStat software (23).

Multiple Factor Analysis (MFA) and biplot graphics were used to explore relationships among elemental composition, sensory descriptors, and qualitative variables such as soil type and vintage. The analysis integrated two datasets, the elemental content matrix and the sensory variable matrix, into a unified framework, using the FactoMineR package in R (1, 34). Two biplots were generated: the first considered soil type as an active variable and vintage as a supplementary variable, highlighting the impact of soil type on the analysis. The second combined both, the elemental and sensory datasets. Aromatic Persistence, Varietal Typicity, and Global Quality descriptors were excluded, following Abdi *et al.* (2013), as these variables reflect taster preferences. Additionally, the biplot emphasized the 10 variables with the highest contribution percentages.

Results

Soil physicochemical traits and grapevine growth

The analysis revealed significant differences in physicochemical properties between the two soil types, except for pH. Shallow soils (SS) contained 18.6% more sand than deep soils (DS), while DS had 97.8% more clay and 88.8% more silt. Additionally, DS exhibited a 78% higher CEC and greater water retention capacity at all measured points (Ws, Wc, and Wm), with increases of 16.9%, 28.4%, and 33.4%, respectively (table 2, page 7).

Table 2. Soil water holding capacity (as indicated by Ws, saturated water point; Wc, field capacity; Wp, permanent wilting point), extractable soil water (RU), soil texture (clay, silt, and sand) and soil cation exchange capacity (CEC).

Tabla 2. Capacidad de retención de agua del suelo (indicado por Ws, punto de saturación. Wc, capacidad de campo; Wp, punto de marchitez permanente), agua extraíble del suelo (RU), textura del suelo (arcilla, limo y arena) y capacidad de intercambio catiónico del suelo (CEC).

Treatments	Ws (g%g)	Wc (g%g)	Wp (g%g)	RU (mm)	Clay (%)	Silt (%)	Sand (%)	CEC (meq%g)	pH
Deep soil	32.59 a	15.33 a	8.10 a	7.82 a	10.64 a	17.33 a	71.98 b	15.27 a	6.74 b
Shallow soil	27.89 b	11.94 b	6.07 b	4.38 b	5.38 b	9.18 b	85.40 a	8.58 b	6.79 ab
***P*-value**	0.0001	0.0001	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0735

Values are means and different letters within each factor and column indicate statistically significant differences (p≤ 0.05, Kruskall-Wallis test).

Los valores son medias, y letras diferentes dentro de cada factor y columna indican diferencias estadísticamente significativas (p≤ 0,05, prueba de Kruskal-Wallis).

Regarding vegetative growth and yield components, DS plants generally showed higher vegetative growth indices, with pruning weight (153%), shoot length (29%), internode length (25%), and shoot diameter (19%) exceeding those of SS vines. No significant differences were observed in yield, number of berries per bunch, or average berry weight between the two soil types. However, DS plants produced 12% more bunches per plant, while SS plants had 25% higher average bunch weight. The Ravaz index indicated an imbalance in DS plants, with values below 5, largely influenced by the 2017 season, suggesting that DS plants exhibit greater vegetative growth relative to berry production. In contrast, SS plants demonstrated more balanced values (table 3, page 8).

The season significantly influenced all analyzed variables. Pruning weight per plant in 2017 was 84% higher compared to the average of the 2018 and 2019 seasons. Yield per plant in 2017 was 50.6% lower than in 2019, which recorded the highest yield of the analyzed period. The 2019 season saw an average increase of 9 more bunches per plant, along with a higher average bunch weight, a greater number of berries per bunch, and a higher average berry weight compared to 2017. The interaction between soil type and season was significant for pruning weight, yield, number of bunches per plant, bunch weight, and berry weight. Pruning weight was consistently higher in DS plants across all years, with the largest difference observed in 2017, where DS had 187% higher pruning weight than SS. Conversely, yield responses varied by soil type and season. In 2017, SS yielded 43% less than DS, while in 2019, DS produced 33% more yield than SS. The number of bunches per plant also fluctuated based on soil type across the three years. In 2017, DS had 21.4% fewer bunches per plant than SS, but in 2018 and 2019, DS plants produced 29.2% and 27.1% more bunches, respectively. Bunch weight was significantly lower in DS during 2017 and 2018, with reductions of 28% and 38%, respectively. Berry weight only showed significant differences in 2018, where DS was 21% lower than SS.

Table 3. Multifactorial ANOVA of vegetative growth and yield components of plants growing in shallow (SS) and deep soils (DS), during 2017-2019 seasons.

Tabla 3. ANOVA multifactorial del crecimiento vegetativo y componentes de rendimiento de plantas en suelos cortos (SS) y profundos (DS), durante las temporadas de 2017-2019.

Treatments	Pruning weight (g)	Shoot length (m)	Internode length (cm)	Shoot width (mm)	Yield (kg pl^{-1})	Bunches per plant	Bunch weight (g)	Berries per bunch	Berry weight (g)	Ravaz index
Deep soil	710.84 a	118.75 a	5.06 a	7.17 a	1.20 a	22.76 a	48.60 b	47.22 a	1.46 a	2.20 b
Shallow soil	281.37 b	91.90 b	4.04 b	6.05 b	1.27 a	20.31 b	60.71 a	55.92 a	1.56 a	5.35 a
2017	712.54 a	117.39 a	6.15 a	7.37 a	0.85 c	17.55 b	45.55 b	47.63 b	1.44 b	1.79 b
2018	398.13 b	100.80 b	2.96 c	6.25 b	1.14 b	20.25 b	55.27 a	46.64 b	1.48 ab	4.40 a
2019	377.64 b	97.78 b	4.54 b	6.21 b	1.72 a	26.81 a	63.15 a	60.44 a	1.60 a	5.14 a
Deep soil*2017	1056.41 a	129.02 a	6.91 a	7.98 a	0.62 d	15.44 d	38.16 d	36.94 b	1.46 b	0.67 d
Shallow soil*2017	368.67 c	105.77 b	5.38 b	6.77 b	1.08 bc	19.65 bc	52.94 bc	58.31 a	1.42 b	2.90 cd
Deep soil*2018	585.26 b	119.23 a	3.27 de	6.93 b	1.02 c	22.83 b	42.48 cd	44.94 ab	1.41 b	1.87 cd
Shallow soil*2018	211.00 d	82.37 c	2.65 e	5.57 c	1.25 bc	17.67 cd	68.05 a	48.33 ab	1.79 a	6.93 a
Deep soil*2019	490.83 b	108.00 b	4.99 bc	6.61 b	1.97 a	30.00 a	65.17 ab	59.78 a	1.50 b	4.05 bc
Shallow soil*2019	264.44 cd	87.56 c	4.09 cd	5.82 c	1.48 b	23.61 b	61.14 ab	61.11 a	1.46 b	6.23 ab
p(soil)	<0.0001	<0.0001	0.0046	<0.0001	0.5917	0.0353	0.0012	0.0695	0.0797	0.0003
p(season)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0007	0.0326	0.0696	0.0032
p(soil*season)	<0.0001	0.0931	0.5587	0.1403	0.0039	0.0004	0.0044	0.1730	0.0028	0.2308

The Values are means (n = 18) and different letters between each factor indicate statistical differences (p ≤ 0.05, LSD Fisher).
Los valores son medias (n = 18), y letras diferentes entre cada factor indican diferencias estadísticas (p ≤ 0,05, prueba LSD de Fisher).

Elemental composition of soil and wine

There were no significant differences in the total elemental concentrations between DS and SS soils. However, specific elements showed notable variations: SS contained higher levels of calcium [Ca], while DS had greater concentrations of manganese [Mn] and potassium [K]. The average concentrations of major elements in both soil types followed the order Mg > Ca > K, and for trace elements, Fe > Al > Na > Mn > Zn > Cu > Rb > Li > Cd (table 4, page 9) .

Considering wines, no significant differences were observed in total elemental concentrations between soil types. However, wines from DS-grown plants exhibited higher levels of iron [Fe], manganese [Mn], and copper [Cu] compared to those from SS-grown plants. The concentrations of major elements in the wines followed the order K > Mg > Ca. For trace elements, wines from DS plants showed the order Na > Fe > Al > Mn > Rb > Cu > Li > Cd, whereas wines from SS plants followed Na > Al > Fe > Rb > Mn > Cu > Li > Cd. Notably, [Zn] concentrations in wines were below the detection limit for both soil types (table 4, page 9).

Descriptive sensory evaluation of wine

The visual descriptors indicated that soil type influenced the intensity of certain characteristics. SS wines exhibited greater color intensity and a more pronounced violet hue than DS wines (table 5, page 9-10). In terms of aromas, SS wines displayed more intense mineral notes, as well as plum aromas, compared to DS wines (table 5, page 9-10). For taste descriptors, SS wines were characterized by greater astringency, structure, varietal typicity, and overall quality than DS wines. In contrast, DS wines had a more pronounced sensation of acidity (table 5, page 9-10).

Table 4. Nonparametric analysis of variance (Kruskal Wallis) for elemental content in soil and Malbec wines (mg L^{-1}).

Tabla 4. Análisis de varianza no paramétrico (Kruskal-Wallis) para el contenido elemental en suelos y vinos Malbec (mg L^{-1}).

Treatments	K	Ca	Mg	Fe	Mn	Cu	Zn
Soil							
Deep	10.04 a	31.61 b	162.74 a	44.71 a	1.35 a	0.07 a	0.15 a
Shallow	8.33 b	54.13 a	154.51 a	42.93 a	1.06 b	0.10 a	0.14 a
Wine							
Deep	1072.46 a	14.61 a	21.42 a	1.20 a	0.71 a	0.06 a	-
Shallow	1018.63 a	14.56 a	20.39 a	0.68 b	0.52 b	0.04 b	-
***P*-value**							
Soil	0.0260	0.0043	0.2403	0.6991	0.0152	0.6991	0.3939
Wine	0.9734	0.8951	0.8432	0.0046	0.0001	0.0479	-

	Na	Al	Li	Rb	Cd	Total
Deep	1.89 a	18.25 a	0.02 a	0.05 a	8.00E-04 a	270.89 a
Shallow	1.67 a	15.69 a	0.02 a	0.04 a	7.30E-04 a	273.21 a
Wine						
Deep	11.65 a	1.10 a	0.04 a	0.61 a	1.10E-03 a	1123.86 a
Shallow	12.90 a	0.99 a	0.04 a	0.57 a	5.70E-04 a	1069.32 a
***P*-value**						
Soil	0.1039	0.0649	0.5887	0.1320	0.3615	>0.9999
Wine	0.3215	0.3913	0.4876	0.1872	0.1419	0.9474

Values are means and different letters within each factor and column indicate a statistically significant difference (p≤0.05, Kruskall Wallis).

Los valores son medias, y letras diferentes dentro de cada factor y columna indican una diferencia estadísticamente significativa (p≤0,05, prueba de Kruskal-Wallis).

Table 5. Intensity of visual, aroma, taste and mouthfeel descriptors of Malbec wines.

Tabla 5. Intensidad de los descriptores visuales, aromáticos, sabor y sensación en boca de los vinos Malbec.

Visual	Clarity	Color intensity	Red hue	Violet hue	Garnet hue	
Deep soil	4.80 a	4.17 b	3.63 a	4.00 b	3.79 a	
Shallow soil	4.70 a	4.49 a	3.65 a	4.31 a	3.58 a	
***P*-value**	0.1676	0.0003	0.7851	0.0037	0.0833	
Aromas	**Mineral**	**Strawberry**	**Plum**	**Cherry**	**Blackberry**	**Violets**
Deep soil	2.69 b	3.36 a	3.69 b	3.37 a	3.53 a	3.61 a
Shallow soil	3.23 a	3.29 a	3.89 a	3.13 a	3.57 a	3.70 a
***P*-value**	<0.0001	0.5818	0.0453	0.0579	0.7253	0.4758
Taste Mouthfeel	**Acidity**	**Sweet**	**Astringency**	**Heat**	**Bitter**	**Structure**
Deep soil	3.56 a	2.79 a	3.00 b	3.04 a	2.93 a	3.07 b
Shallow soil	3.30 b	2.94 a	3.38 a	3.12 a	2.75 a	3.64 a
***P*-value**	0.0084	0.1563	<0.0001	0.4019	0.1119	<0.0001

Values are means and different letters between each factor indicate statistical differences (p ≤ 0.05, LSD Fisher).

Los valores son medias, y letras diferentes entre cada factor indican diferencias estadísticas (p ≤ 0,05, prueba LSD de Fisher).

Aromas	Caramel	Paprika	Vanilla	Chocolate
Deep soil	2.73 a	2.69 a	2.59 a	2.57 a
Shallow soil	2.56 a	2.70 a	2.74 a	2.62 a
***P*-value**	0.2183	0.8834	0.2051	0.6836
Taste Mouthfeel	**Oiliness**	**Harmony**	**Aromatic persistence**	**Varietal typicity**
Deep soil	3.07 a	3.29 a	3.59 a	3.70 b
Shallow soil	3.14 a	3.33 a	3.55 a	3.96 a
***P*-value**	0.4182	0.6253	0.6461	0.0022

Aromas	Liqueur jam	Global intensity
Deep soil	2.96 a	3.56 a
Shallow soil	2.83 a	3.49 a
***P*-value**	0.3754	0.4842

Taste Mouthfeel	Global quality
Deep soil	3.57 b
Shallow soil	4.02 a
***P*-value**	<0.0001

Values are means and different letters between each factor indicate statistical differences ($p \leq 0.05$, LSD Fisher).

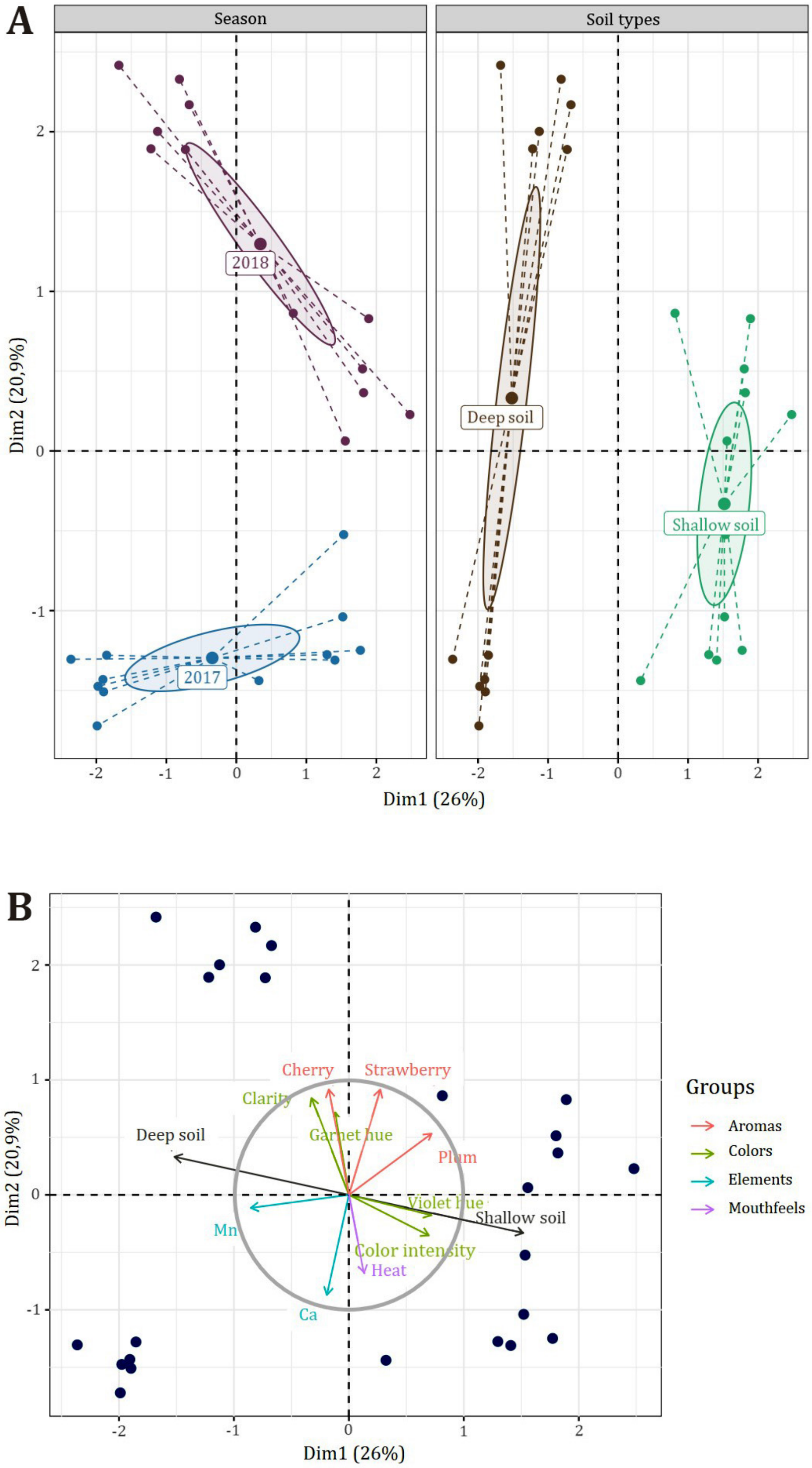
Los valores son medias, y letras diferentes entre cada factor indican diferencias estadísticas ($p \leq 0,05$, prueba LSD de Fisher).

The MFA revealed that wines from DS showed greater variability across vintages, suggesting a stronger influence of interannual conditions on this soil type. In contrast, wines from SS exhibited more consistent characteristics, highlighting the dominant effect of soil type on sensory variables over climatic variations (figure 2 A, page 11).

Among the sensory and elemental variables with the highest contributions were Cherry, Strawberry, Clarity, Garnet hue, Plum, Violet hue, Color intensity, Heat, Mn, and Ca (Figure S3). The analysis combining elemental composition and sensory data highlighted key relationships between quantitative and qualitative variables, such as soil type and vintage. Variables positioned closer to the gray circle (value 1) in the biplot contributed significantly to the model, emphasizing their relevance in the main dimensions. For example, [Ca] was more influenced by vintage than soil type, with 2017 showing a higher accumulation of this element in wines. Conversely, [Mn] was more strongly associated with deep soils, regardless of vintage (figure 2 B, page 11).

In terms of visual descriptors, wines from SS were characterized by higher color intensity and more pronounced violet hues, whereas wines from DS exhibited subtler visual attributes, such as clarity. Considering aromatic descriptors, SS wines were particularly noted for their plum aromas.

Some sensory descriptors, however, appeared to be more influenced by vintage than soil type, likely due to climatic conditions. For instance, cherry and strawberry aromas, as well as the visual descriptor Garnet hue were more closely associated with climatic conditions, especially the 2018 vintage. In contrast, the sensation of heat (linked to higher alcohol content) was primarily associated with the 2017 vintage.



(A) Influence of soil type (active variable) and vintage (supplementary variable) on Dim1 and Dim2, showing greater interannual variability in DS wines compared to SS wines. (B) Biplot integrating elemental and sensory descriptors, highlighting key contributors.

(A) Influencia del tipo de suelo (variable activa) y la añada (variable suplementaria) en Dim1 y Dim2, mostrando una mayor variabilidad interanual en los vinos de DS en comparación con los de SS. (B) Biplot que integra descriptores elementales y sensoriales, destacando los principales contribuyentes.

Figure 2. Multiple Factor Analysis (MFA).

Figura 2. Resultados del Análisis Multifactorial (MFA).

Discussion

Our findings indicate that soil characteristics, such as depth, texture and fertility, have differential effects on vegetative growth, as well as on the elemental composition and sensory profile of Malbec wines. However, yield components did not show a consistent pattern based on soil type, exhibiting variability across seasons. Indicators of vegetative growth, including pruning weight, shoot length, internode length, and shoot width, were strongly correlated with soil depth, with DS displaying superior values across all vigor indicators. These differences in vegetative growth can likely be attributed to variations in water availability, as DS retained higher water content than SS, and these growth indicators are known to be highly sensitive to water deficit (52). This finding is consistent with previous studies conducted in similar areas of the Mendoza foothills, where vines planted in deeper soils exhibited improved growth due to better water retention (42).

Surprisingly, no significant differences in yield were observed between soil types when analyzing the average values across the three studied seasons. However, a strong interaction was found between vigor and production indicators, which varied by season. The 2017 season saw significantly higher vigor in DS plants across all analyzed variables. However, the most productive plants during this season were those in SS, likely due to a greater number of bunches and more berries per bunch. This suggests improved fruit set, reduced berry shatter, and/or lower bunch abortion rates in SS compared to DS plants. As noted earlier, no bunch thinning was performed in the analyzed treatments. Notably, the 2017 season was particularly humid compared to the historical average (Figure S1), which could have influenced the vigor of DS plants, creating an imbalance between vigor and fertility. The imbalance is important, as the Malbec cultivar is prone to shatter and millerandage in vigorous plants (17).

In contrast, the 2018 season was approximately 40% drier than the historical average (Figure S1). The impact of this drier season was primarily observed in reduced internode growth in plants from both soil types, with consistently low values and no significant differences between soils. Yield per plant also showed no differences between soil types. However, SS plants had fewer bunches per plant but higher bunch weights due to greater berry weight, while DS plants produced more bunches per plant but with smaller berries. The drier conditions likely affected bud fertility, fruit set, and bunch necrosis (26) in SS plants, resulting in fewer bunches. During bud primordia development, low water availability may cause floral primordia to dedifferentiate into tendrils, reducing bud fertility and ultimately the number of bunches in the following season (53).

In 2019, the same trend in vigor indicators as in 2018 was observed, although internode length values were higher. This season had slightly more rainfall than the historical average, and the higher yield in DS plants was primarily due to a greater number of bunches per plant. Since both soil types had the same number of buds per vine during pruning, this suggests that soil conditions significantly influence final yield. Reduced bud fertility in SS plants, evidenced by fewer bunches per plant, likely explains the lower yield in this soil type. Additionally, some buds in SS plants failed to break, further contributing to the reduced yields. While soils with higher water-holding capacity often correlate with increased yields (12), studies by van Leeuwen *et al.* (2004) have reported reduced bunch weights in stony soils compared to clay soils. Limited water absorption reduces vegetative growth and production (41, 58), but our results showed no significant differences in yield per plant, number of berries per bunch, or berry weight between soil types. Although differences in bunches per plant and bunch weight were observed across vintages, no clear trend was found. While SS plants had larger bunches in 2017, DS plants exhibited this trait in 2018 and 2019. These variations in yield across vintages are likely due to climatic factors, as the same number of buds was retained during pruning.

Bunches per plant and bunch weight are influenced by various factors, including climatic conditions, soil electrical conductivity, and agricultural management practices (42). The equal number of buds left in plants (14 per plant) in both soil types may have contributed to the observed results. Previous studies suggest that the Malbec cultivar develops compensatory mechanisms between vegetative growth and production, acclimating to the edaphic environment by enhancing hydraulic conductivity in SS. This adaptation may help

Malbec overcome the low water retention capacity in SS (49), which could play a significant role in balancing production across different soil types. However, the Ravaz index, calculated from yield and pruning weight data, indicated that DS plants exhibited excessive vegetative growth relative to production. This finding aligns with previous research (41), which showed that Malbec plants in DS demonstrated greater vegetative growth in relation to yield. In contrast, other studies have reported that SS plants have lower vegetative-to-yield ratios (59). Despite these differences in the Ravaz index between soil types, our study found no significant differences in yield for the Malbec cultivar under the conditions analyzed.

Our study revealed that the elemental profile of soil at intra-vineyard level varies with depth. Soil analysis showed that DS, characterized by a higher proportion of fine particles, increased CEC, and greater water retention, provides a potentially less stressful environment for grapevine growth compared to SS (16). Although SS exhibited significantly higher [Ca], consistent with the high $CaCO_3$ content in the fluvial strata of the Andes (20, 21), no differences in pH were detected between the two soil types, which could influence nutrient absorption (13). The higher [Mn] and [K] observed in DS are consistent with its higher clay content (43). Consequently, DS soils are enriched in Mn and K, whereas SS soils have higher [Ca], potentially influencing nutriment uptake and accumulation in berries, and subsequently in wine, due to antagonistic or synergistic nutrient interactions (43). For example, high potassium levels in soil may enhance manganese uptake (5), while elevated calcium levels may inhibit it (37).

Wines from DS soils showed higher [Mn], [Cu] and [Fe]. Elevated concentrations of Mn in DS soils were also reflected in the wines produced from these soils. Similar findings have been reported by Kment *et al.* (2005), who found that wines from deep, clay-rich soils had higher [Mn] than those from SS (12). Campbell and Nable (1988) explained that plant [Mn] levels are directly influenced by xylem flow (25). Given this and the greater water-holding capacity of DS soil, DS plants likely experience increased [Mn] availability through mass flow, which would explain the higher concentrations of this element in DS wines. Although these observations were made on a regional scale, previous studies have identified Mn as a key element distinguishing wines based on their origin (39).

This study highlighted the significant impact of soil heterogeneity at the intra-vineyard level (micro-scale) on wine, resulting in differential elemental profiles. Although high [Cu] and [Fe] in wines did not correlate with higher concentrations of these elements in DS, the increased [Cu] can be attributed to a potentially greater interception of $CuSO_4$ applications by the canopy, as DS plants have a larger exposed leaf surface. The elevated [Fe] detected in wines may be influenced by several factors, including differential adsorption of dust particles on the epicuticular wax of berries and physiological differences in Fe uptake and allocation within the plant. While the higher vegetative growth in DS plants may alter Fe dynamics, the specific mechanism leading to elevated Fe levels in berries and wines remains unclear. This potential relationship between vegetative growth and Fe accumulation warrants further investigation to confirm a direct causal link. Additionally, our study demonstrated that visual, aroma, and taste descriptors of wine differ depending on soil type at intra-vineyard level. Grape harvest was standardized across all soil types at 24° Brix to ensure uniform maturity levels and minimize sensory differences related to ripeness. Visual descriptors showed that SS wines had greater color intensity and a more pronounced violet hue, consistent with previous findings (41), reporting higher total anthocyanin concentrations in Malbec berries grown under similar SS conditions. Bramley *et al.* (2011) similarly observed greater color intensity in Cabernet Sauvignon wines from shallow soils. The quantity and composition of anthocyanins in wines directly affect color intensity and tonality, and are influenced by factors such as water restrictions, yield, plant vigor, temperature, and soil characteristics like texture and stone volume (18, 45). Furthermore, wine color is also influenced by pH, as lower pH values favor the proportion of anthocyanins in the form of flavylium cation (22). However, during the winemaking process, the pH was standardized to 3.75 for all wines, which likely minimized potential color differences related to pH.

Water deficit, depending on intensity and the phenological stage, can increase anthocyanin and tannin content in berries (60). This effect is primarily attributed to increased production of abscisic acid (ABA) in response to water stress, which stimulates anthocyanin biosynthesis (7). The higher color intensity observed in SS wines aligns with the more stressful water conditions typically associated with this soil type (Figure S2).

Additionally, the greater color intensity may be influenced by vegetative expressions in each soil type, and high-altitude vineyard conditions. Indicators such as pruning weight, shoot length, internode length, and shoot width suggest that DS plants exhibit greater vegetative growth , which could result in increased berry shading. In contrast, the reduced vegetative growth in SS plants likely leads to greater exposure of the berries to solar radiation.

Previous studies conducted in a nearby vineyard demonstrated that Malbec berries exposed to higher UV-B radiation accumulated higher concentrations of total anthocyanins than those exposed to reduced UV-B (8). The intensified violet hue observed may result from copigmentation effects, in which molecular associations between anthocyanins and other organic molecules, such as myricetin or caffeic acid, induce a color shift towards violet (9). McDonald *et al.* (1998) noted that the concentration of flavonols, such as myricetin, may vary depending on geographical origin and could be higher in thick-skinned berries. Furthermore, Berli *et al.* (2008) reported increased flavonols, such as quercetin, myricetin, and kaempferol, in vineyards exposed to higher UV-B radiation. These compounds, powerful antioxidants, accumulate either through direct stimulation of their synthesis or indirectly by increasing berry skin thickness, enhancing their concentration (53). However, further studies are required to validate these findings, as berry skin thickness and specific flavonol concentrations were not measured in this study.

Regarding aromas, SS wines exhibited more intense plum aromas, which are commonly associated with fruit characteristics (44). This finding aligns with Bramley *et al.* (2011), who reported higher concentration of volatile compounds associated with fruity aromas in SS wines. Additionally, Chapman *et al.* (2005) found that wines from vineyards subjected to water deficit tend to have more pronounced fruity aromas and flavors. Furthermore, SS wines were characterized by a higher intensity of mineral notes, which the tasting panel described as a "wet stone" aroma. Although this specific descriptor is not explicitly listed in the aromatic wheel of Noble *et al.* (1987), it is generally referred to as a mineral note. Panelists described these aromas as reminiscent of crushed stones, rocks, wet cement, chalk, gravel, or limestone (26). While such descriptors are often associated with wines from stony soils and are sometimes referred to as "rich in minerals", it is important to note that berries have limited direct chemical interaction with soil minerals, and minerals themselves are odorless, so they cannot contribute directly to wine aroma (35). Our study found no differences in total elemental content between the two soil types or the wines they produced, suggesting that the mineral aroma in wine does not stem from a higher elemental content. Tominaga *et al.* (2003) suggested that benzene methane thiol (benzyl mercaptan) could contribute to mineral aromas in wine, but further research is needed to better understand the origins of these sensory characteristics.

Concerning taste descriptors, SS wines exhibited greater astringency and structure, suggesting water stress plays a significant role in promoting tannins concentration (flavanol polymers) in berries, which are primarily responsible for astringency sensations (4). This observation is supported by Figure S2, which shows that SS plants experienced moderate water stress compared to DS plants. This was previously found by Mezzatesta *et al.* (2022), who reported higher total polyphenol content in SS berries. Wine structure is influenced by three key components: tannins, acidity, and alcohol (18). Although the acidity sensation in SS wines was significantly lower than in DS wines, the heightened astringency may have contributed to a more pronounced structure in SS wines. Wine typicity refers to the specific varietal organoleptic traits, which can be modified by the unique characteristics of the terroir (18). In the case of SS wines, the attributes of this soil favored the varietal expression of Malbec, enhancing plum notes with a slight tendency towards violet aromas, typical of this cultivar (18). Finally, the higher overall quality attributed to Malbec SS wines likely stems from the combination of sensory attributes distinguishing these wines. In general, sensory analyses support the assertion by Bramley and Hamilton (2007) that wines originating from delineated areas within the same parcel, uniformly managed according inherent vigor and yield propensity, exhibit distinct sensory profiles.

According to this study, evidence suggests that the significant heterogeneity of intra-vineyard soils generates distinct sensory profiles, with soil type playing a predominant role. SS soils were linked to vineyards experiencing water stress, leading to distinct sensory profiles. Identifying and distinguishing soil types within a vineyard and adjusting harvesting practices accordingly could result in wines with diverse sensory profiles.

MFA highlighted the interactions between the edaphic characteristics and interannual climatic conditions in shaping elemental wine composition and sensory attributes. The greater variability observed in DS wines across vintages emphasizes the sensitivity of this soil type to climatic conditions, such as differences in precipitation and water stress between 2017 and 2018 (Figures S1 and S2). In contrast, wines from SS exhibited more consistent sensory characteristics, suggesting that soil properties largely influenced climatic factors.

The variation in [Ca] across vintages, with higher accumulation in 2017, could be attributed to the elevated precipitation during that season, which likely favored the availability and transport of Ca to the berries (62). In contrast, the [Mn], more strongly associated with DS irrespective of vintage, may be linked to the higher clay content in these soils, which, combined with their greater water retention capacity, influences plant absorption and accumulation of this element (45). These differences in elemental composition reflect soil-climate interactions and contribute to the observed variations in sensory descriptors.

In sensory terms, wines from SS stood out for their higher color intensity and fruity aromas, such as plum, which were likely amplified by the moderate to severe water stress experienced in these soils. In contrast, wines from DS, while exhibiting subtler visual attributes (clarity) displayed greater variability in descriptors like cherry and strawberry, particularly in 2018, a drier season that may have heightened these attributes. Additionally, Mn, a key element influencing wine color due to its ability to form stable complexes with amino acids and polyphenols (56), showed a negative association with color intensity and violet hue. This contrasts with the findings of Mantilla *et al.* (2018), who reported greater color intensity in Shiraz wines with higher Mn levels. This discrepancy underscores how soil properties modulate the impact of climatic conditions on wine quality, emphasizing the importance of differentiated management strategies to optimize both productivity and sensory profiles.

Finally, the associations of descriptors such as "Garnet hue" or "Heat" with specific climatic conditions highlight vintage significance in shaping the final wine profile, particularly in soils like DS, which are more responsive to interannual variations. These observations reinforce the need to understand soil-climate dynamics to interpret and predict how these interactions influence wine quality and terroir expression.

Conclusions

The significant intra-vineyard soil heterogeneity in high-altitude plantations located in the foothills of the central Andes influence both elemental and sensory profiles of wines. While Malbec yield was not distinctly affected by soil type, probably given climatic variations across growing seasons, there were notable differences in vegetative expression between shallow and deep soils. Although we confirmed that wine elemental profile is influenced by soil characteristics, further studies should stablish its direct impact on sensory attributes. This is crucial for winemakers aiming to diversify their blends or produce distinct wines from the same vineyard under the single parcel concept.

It is important to clarify that this study does not propose management strategies to increase or decrease vine vigor based on soil type. Instead, we aimed to examine the effect of relatively homogeneous but contrasting soil sections on grapevines and wine quality. The findings may contribute to developing management strategies in Argentinian Malbec vineyards that optimize parcel shapes and sizes according to soil type, facilitating the production of wines with unique elemental and sensory profiles on a small scale. Moreover, further research on Malbec phenotypic plasticity and its relationship with elemental composition and sensory properties will have significant implications for both viticulture and oenology, offering valuable insights for the winemaking industry.

Supplemmentary material:

https://docs.google.com/document/d/1KBl4hw-zz1HOfLjLNbTlLK12dSA2q-pd/edit?usp=sharing&ouid=111310786017351827239&rtpof=true&sd=true

References

1. Abdi, H.; Williams, L. J.; Valentin, D. 2013. Multiple factor analysis: Principal component analysis for multitable and multiblock data sets. Wiley Interdisciplinary Reviews: Computational Statistics. 5(2): 149-179. https://doi.org/10.1002/wics.1246
2. Almeida, C.; Vasconcelos, M. 2003. Multielement composition of wines and their precursors including provenance soil and their potentialities as fingerprints of wine origin. Journal of Agricultural and Food Chemistry. 51(16): 4788-4798. https://doi: 10.1021/jf034145b
3. Arias, L. A.; Berli, F.; Fontana, A.; Bottini, R.; Piccoli, P. 2022 Climate change effects on grapevine physiology and biochemistry: Benefits and challenges of high altitude as an adaptation strategy. Frontiers in Plant Science. 13: 835425. https://doi: 10.3389/fpls.2022.835425
4. Attia, F.; Garcia, F.; Ben Mariem, F.; Nuzzo, V.; Dedieu, F.; Garcia, M.; Lamaze, T. 2010. Water stress in Tannat and Duras grapevine cultivars (*Vitis vinifera* L.): Leaf photosynthesis and grape phenolic maturity. Journal International des Sciences de la Vigne et du Vin. 6: 81-93.
5. Ayamba B. E.; Abaidoo R. C.; Opoku A.; Ewusi-Mensah N. 2023. Mechanisms for nutrient interactions from organic amendments and mineral fertilizer inputs under cropping systems: A review. PeerJ. 11: e15135. https://doi:10.7717/peerj.15135
6. Baggiolini M. 1952. Les stades repères dans le développement annuel de la vigne et leur utilisation pratique. Revue romande d'Agriculture et d'Arboriculture. 8(1): 4-6.
7. Berli, F.; D'Angelo, J.; Cavagnaro, B.; Bottini, R.; Wuilloud, R.; Silva, M. F. 2008 Phenolic composition in grape (*Vitis vinifera* L. cv. Malbec) ripened with different solar UV-B radiation levels by capillary zone electrophoresis. Journal of Agricultural and Food Chemistry. 56: 2892-2898. https://doi: 10.1021/jf073421+
8. Berli, F.; Alonso, R.; Beltrano, J.; Bottini, R. 2015. High altitude solar UV-B and abscisic acid sprays increase grape berry antioxidant capacity. American Journal of Enology and Viticulture. 66(1): 65-72. https://doi.org/10.5344/ajev.2014.14067
9. Boulton, R. 1999. El fenómeno de la copigmentación en los vinos tintos. Actas Seminario Internacional "Hacia la Enología del siglo XXI". INTA, Facultad de Ciencias Agrarias. Universidad Nacional de Cuyo. Argentina.
10. Bouyoucos, G. J. 1951. A recalibration of the hydrometer method for making mechanical analysis of soils. Agronomy Journal. 43(9): 434-438.
11. Bramley, R. G. V.; Hamilton, R. P. 2007. Terroir and precision viticulture: are they compatible? Journal International des Sciences de la Vigne et du Vin. 41: 1-8. https://doi.org/10.20870/oenoone.2007.41.1.855
12. Bramley, R.; Ouzman, J.; Boss, P. 2011. Variation in vine vigour, grape yield and vineyard soils and topography as an indicator of variation in the chemical composition of grapes, wine and wine sensory attributes. Australian Journal of Grape and Wine Research. 17(2): 217-229. https://doi.org/10.1111/j.1755-0238.2011.00136.x
13. Bravo, S.; Amoros, J. A.; Perez-De-Los-Reyes, C.; García, F. J.; Moreno, M. M.; Sanchez-Ormeno, M.; Higueras, P. 2017. Influence of the soil pH in the uptake and bioaccumulation of heavy metals (Fe, Zn, Cu, Pb and Mn) and other elements (Ca, K, Al, Sr and Ba) in vine leaves. Castilla-La Mancha (Spain). Journal of Geochemical Exploration. 174: 79-83. https://doi.org/10.1016/j.gexplo.2015.12.012
14. Bruand, A.; Duval, O.; Cousin, I. 2004. Estimation des propriétés de rétention en eau des sols à partir de la base de données SOLHYDRO: Une première proposition combinant le type d'horizon, sa texture et sa densité apparente. Étude et gestion des Sols. 11(3): 3-323.
15. Campbell, L. C.; Nable, R. O. 1988. Physiological functions of manganese in plants. In: Graham, R. D.; Hannam, R. J.; Uren N. C. (Eds.). Manganese in soils and plants. Kluwer Academic Publishers: Dordrecht. 139-154. https://doi.org/10.1007/978-94-009-2817-611
16. Caravaca, F.; Lax, A.; Albaladejo, J. 1999. Organic matter, nutrient contents and cation exchange capacity in fine fractions from semiarid calcareous soils. Geoderma. 93: 161-176. https://doi.org/10.1016/S0016-7061(99)00045-2
17. Carrillo, N.; Piccoli, P.; Bottini, R.; Rodríguez, J.; Berli, F. 2020. Girdling of shoots at flowering reduces shatter in grapevine cv. Malbec. Australian Journal of Grape and Wine Research. 26(2): 102-109. https://doi.org/10.1111/ajgw.12423
18. Catania, C. D.; Avagnina, S. 2010. La interpretación sensorial del vino. In: El terruño argentino. INTA y Editora Andina Sur.
19. Chapman, D. M.; Roby, G.; Ebeler, S. E.; Guinard, J. X.; Matthews, M. A. 2005. Sensory attributes of Cabernet Sauvignon wines made from vines with different water status. Australian Journal of Grape and Wine Research. 11(3): 339-347. https://doi:10.1111/j.1755-0238.2005.tb00033.x
20. Chavez, D. 2013. Groundwater potential of pampa aquifers in two glacial watersheds, Cordillera Blanca, Peru. Master Science Thesis. McGill University, Montreal. Quebec. Canada. 69 p.
21. Corona, G. 2019. La geografía del vino. In: Malher, P. (Ed.). Ciudad Autónoma de Buenos Aires. Argentina.
22. de Freitas, V. A. P.; Fernandes, A.; Oliveira, J.; Teixeira, N.; Mateus, N. 2017. A review of the current knowledge of red wine colour. OENO One. 51: 1. https://doi.org/10.20870/oenoone.2017.51.1.1604

23. Di Rienzo, J. A.; Casanoves, F.; Balzarini, M. G.; González, L.; Tablada, M.; Robledo, C. W. 2018. InfoStat (versión 2018) [Software]. Universidad Nacional de Córdoba, Argentina. http://www.infostat.com.ar
24. Funes Pinter, I.; Salomon, M. V.; Gil, R.; Mastrantonio, L.; Bottini, R.; Piccoli, P. 2018. Arsenic and trace elements in soil, water, grapevine and onion in Jachal, Argentina. Science of the Total Environment. 615: 1485-1498. https://doi.org/10.1016/j.scitotenv.2017.09.114
25. Galani-Nikolakaki, S.; Kallithrakas-Kontos, N.; Katsanos, A. A. 2002. Trace element analysis of Cretan wines and wine products. Science of the Total Environment. 285(1-3): 155-163. https://doi:10.1016/S0048-9697(01)00912-3
26. Guilpart, N.; Metay, A.; Gary, C. 2014. Grapevine bud fertility and number of berries per bunch are determined by water and nitrogen stress around flowering in the previous year. European Journal of Agronomy. 54: 9-20. https://doi.org/10.1016/j.eja.2013.11.002
27. Heymann, H.; Hopfer, H.; Bershaw, D. 2014. An exploration of the perception of minerality in white wines by projective mapping and descriptive analysis. Journal of Sensory Studies. 29(1): 1-13. https://doi:10.1111/joss.12076
28. Hidalgo, J. 2006. La calidad del vino desde el viñedo. In: Ediciones Mundi-Prensa. Madrid.
29. Hilbert, G.; Soyer, J. P.; Molot, C.; Giraudon, J.; Milin, S.; Gaudillere, J. P. 2003. Effects of nitrogen supply on must quality and anthocyanin accumulation in berries of cv. Merlot. Vitis. 42(2): 69-76. https://doi.org/10.5073/vitis.2003.42.69-76
30. INV. 2023. Informe anual de superficie 2023. https://www.argentina.gob.ar/inv/vinos/estadisticas/superficie/anuarios
31. Kabata-Pendias, A. 2011. Trace elements of soils and plants. In: CRC Press, Taylor & Francis Group.
32. Kment, P.; Mihaljevič, M.; Ettler, V.; Šebek, O.; Strnad, L.; Rohlová, L. 2005. Differentiation of Czech wines using multi element composition - A comparison with vineyard soil. Food Chemistry. 91(1): 157-165. https://doi:10.1016/j.foodchem.2004.06.010
33. Lawless, H. T.; Heymann, H. 2010. Sensory evaluation of food - principles and practices. In: Sensory Evaluation of Food-Principles and Practices. p. 473-478.
34. Lê, S.; Josse, J.; Husson, F. 2008. FactoMineR: An R Package for Multivariate Analysis. Journal of Statistical Software. 25(1): 1-18. https://doi.org/10.18637/jss.v025.i01
35. Maltman, A. 2008. The role of vineyard geology in wine typicity. Journal of Wine Research. 19(1): 1-17. https://doi:10.1080/09571260802163998
36. Maltman, A. 2013. Mineral taste in wine, minerals in the vineyard are they connected? Wines and Vines. 94(5): 63.
37. Malvi, U. R. 2011. Interaction of micronutrients with major nutrients with special reference to potassium. Karnataka Journal of Agricultural Sciences. 24(1): 106-109.
38. Mantilla, S. M. O.; Collins, C.; Iland, P. G.; Kidman, C. M.; Ristic, R.; Boss, P. K.; Jordans, C.; Bastian, S. E. 2018. Shiraz (*Vitis vinifera* L.) berry and wine sensory profiles and composition are modulated by rootstocks. American Journal of Enology and Viticulture. 69(1): 32-44. https://doi: 10.5344/ajev.2017.17017
39. Marengo, E.; Aceto, M. 2003. Statistical investigation of the differences in the distribution of metals in Nebbiolo-based wines. Food Chemistry. 81(4): 621-630. https://doi:10.1016/S0308-8146(02)00564-2
40. McDonald, M. S.; Hughes, M.; Burns, J.; Lean, M. E. J.; Matthews, D.; Crozier, A. 1998. Survey of the free and conjugated myricetin and quercetin content of red wines of different geographical origins. Journal of Agricultural and Food Chemistry. 46(2): 368-375. https://doi:10.1021/jf970677e
41. Mezzatesta, D. S.; Berli, F.; Arancibia, C.; Buscema, F.; Piccoli, P. 2022. Impact of contrasting soils in a high-altitude vineyard of *Vitis vinifera* L. *cv.* Malbec: root morphology and distribution, vegetative and reproductive expressions, and berry skin phenolics. OENO One. 56(2): 149-163. https://doi.org/10.20870/oeno-one.2022.56.2.4917
42. Monteiro, A.; Malheiro A.; Bacelar, E. (2021). Morphology, physiology and analysis techniques of grapevine bud fruitfulness: A Review. Agriculture. 11(2): 127. https://doi.org/10.3390/agriculture11020127
43. Mousavi, S. R.; Shahsavari, M.; Rezaei, M. 2011. A general overview on manganese (Mn) importance for crop production. Australian Journal of Basic and Applied Sciences. 5(9): 1799-1803.
44. Noble, A. C.; Arnold, R. A.; Buechsenstein, J.; Leach, E. J.; Schmidt, J. O.; Stern, P. M. 1987. Modification of a standardized system of wine aroma terminology. American Journal of Enology and Viticulture. 38(2): 143-146.
45. Ojeda, H. 2000. Los compuestos polifenólicos de la uva. In: EEA Mendoza. INTA.
46. Oliveira, C.; Ferreira, A. C.; Costa, P.; Guerra, J.; Guedes de Pinho, P. 2004. Effect of some viticultural parameters on the grape carotenoid profile. Journal of Agricultural and Food Chemistry. 52: 4178-4184. https://doi: 10.1021/jf0498766
47. Pirie, A.; Mullins, M. G. 1976. Changes in anthocyanin and phenolics content of grapevine leaf and fruit tissues treated with sucrose, nitrate, and abscisic acid. Plant Physiology. 58: 468-472. https://doi.org/10.1104/pp.58.4.468
48. QGIS Development Team. 2020. QGIS Geographic Information System. Open Source Geospatial Foundation. https://qgis.org

49. Richards, L. A. 1954. Diagnosis and improvement of saline and alkali soils. United States Salinity Laboratory Staff. Agriculture 160. Handbook 60. https://www.ars.usda.gov/ARSUserFiles/20360500/hb60_pdf/hb60complete.pdf
50. Roig-Puscama, F.; Berli, F.; Roig, F. A.; Tomazello-Filho, M.; Mastrantonio, L.; Piccoli, P. 2021. Wood hydrosystem of three cultivars of *Vitis vinifera* L. is modified in response to contrasting soils. Plant and Soil. 463: 573-588. https://doi.org/10.1007/s11104-021-04907-y
51. Scholander, P. F.; Hammel, H. T.; Bradstreet, E. D.; Hemmingsen, E. A. 1965. Sap pressure in vascular plants. Science. 148(3668): 339-346. https://doi.org/10.1126/science.148.3668.339
52. Silva-Contreras, C.; Sellés-Von Schouwen, G.; Ferreyra-Espada, R.; Silva-Robledo, H. 2012. Variation of water potential and trunk diameter answer as sensitivity to the water availability in table grapes. Chilean Journal of Agricultural Research. 72(4): 459-469. https://doi:10.4067/S0718-58392012000400001
53. Srinivasan, C.; Mullins, M. G. 1981. Physiology of flowering in the grapevine-a review. American Journal of Enology and Viticulture. 11(1): 47-63. https://doi.org/10.5344/ajev.1981.32.1.47
54. Stockley, C. S.; Høj, P. B. 2005. Better wine for better health: Fact or fiction? Australian Journal of Grape and Wine Research. 11(2): 127-138. https://doi.org/10.1111/j.1755-0238.2005.tb00284.x
55. Tariba, B. 2011. Metals in wine-Impact on wine quality and health outcomes. Biological Trace Element Research. 144(1-3): 143-156. https://doi:10.1007/s12011-011-9052-7
56. Tomasi, N.; Monte, R.; Varanini, Z.; Cesco, S.; Pinton, R. 2015. Induction of nitrate uptake in Sauvignon Blanc and Chardonnay grapevines depends on the scion and is affected by the rootstock. Australian Journal of Grape and Wine Research. 21(2): 331-338. https://doi.org/10.1111/ajgw.12137
57. Tominaga, T.; Guimbertau, G.; Dubourdieu, D. 2003. Contribution of benzenemethanethiol to smoky aroma of certain *Vitis vinifera* L. wines. Journal of Agricultural and Food Chemistry. 51(5): 1373-1376. https://doi:10.1021/jf020756c
58. van Leeuwen C. 2010. Terroir: the effect of the physical environment on vine growth, grape ripening and wine sensory attributes. In: Reynolds A. (Ed.). Managing wine quality. Woodhead publishing series in food science, technology and nutrition, p. 273-315. http://dx.doi.org/10.1533/9781845699284.3.273
59. van Leeuwen, C.; Friant, P.; Choné, X.; Tregoat, O.; Koundouras, S.; Dubourdieu, D. 2004. Influence of climate, soil, and cultivar on terroir. American Journal of Enology and Viticulture. 55: 207-217. https://doi.org/10.5344/ajev.2004.55.3.207
60. van Leeuwen, C.; Seguin, G. 2006. The concept of terroir in viticulture. Journal of Wine Research. 17: 1-10. https://doi.org/10.1080/09571260600633135
61. van Leeuwen, C.; Tregoat, O.; Choné, X.; Bois, B.; Pernet, D.; Gaudillère, J. P. 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? Journal International des Sciences de la Vigne et du Vin. 43: 121-134. https://doi.org/10.20870/oeno-one.2009.43.3.798
62. White, P. J.; Broadley, M. R. 2003. Calcium in plants. Annals of Botany. 92(4): 487-511. https://doi.org/10.1093/aob/mcg164

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