Natural and environmental resources

Montmorillonite content is an influential soil parameter of grapevine development and yield in South Uruguay

El contenido de montmorillonita es un parámetro de suelo influyente en el desarrollo y rendimiento de la vid en el sur de Uruguay

O teor de montmorilonite é um parâmetro influente do desenvolvimento e rendimento da videira no Sul do Uruguai

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Abstract: Soil physical and chemical characteristics play a key role on vine growth and yield. The soils of South Uruguay display high content of montmorillonite or illite. The proportion of these minerals deserves special attention as they influence the soil structure and its hydrological properties. The present study was conducted in a 1.1 ha vineyard of this region (Canelones), characterized by a high heterogeneity of plant vigour. It was aimed to determine and map the physical and chemical properties of the soil and their relations with plant vigour and yield. The cation exchange capacity (CEC) and the clay and organic matter contents were measured in 84 locations within this vineyard to calculate the montmorillonite and illite contents of the soil. In addition, the type and abundance of clays was corroborated by X-ray diffractometry analysis. The CEC and montmorillonite contents were positively correlated with vine vigour, expressed by the Normalized Vegetation Index (NDVI), trunk diameter, pruning weight, leaf area, and with yield. Thus, the within vineyard distribution of the ratio montmorillonite/illite conditioned the heterogeneity of vine growth and yield at the field level. The impact of those minerals on water and mineral supply to the plant is discussed.

Keywords: clay type 2:1, CEC, verticargiudol, soil heterogeneity.

Resumen: Las características físicas y químicas del suelo desempeñan un papel fundamental en el crecimiento y el rendimiento de la vid. Los suelos del sur de Uruguay presentan un alto contenido de montmorillonita o illita. Las proporciones de estos minerales merecen especial atención ya que influyen en la estructura del suelo y en sus propiedades hídricas. El presente estudio se realizó en un viñedo de 1,1 ha de esta región (Canelones), caracterizado por una alta heterogeneidad de vigor de las plantas. El objetivo fue determinar y cartografiar las propiedades físicas y químicas del suelo, y su relación con el vigor de las plantas y el rendimiento. La capacidad de intercambio catiónico (CEC) y los contenidos de arcilla y materia orgánica se midieron en 84 lugares de este viñedo para calcular los contenidos de montmorillonita e illita del suelo. Además, se corroboró el tipo y la abundancia de arcillas mediante análisis de difractometría de rayos X. Los contenidos de CEC y de montmorillonita se correlacionaron positivamente con el vigor de la vid, expresado por el índice de vegetación normalizado (NDVI), el diámetro del tronco, el peso de la poda, el área foliar y con el rendimiento. Así, la distribución dentro del viñedo de la relación montmorillonita/ilita condicionó la heterogeneidad del crecimiento de la vid y del rendimiento a nivel de campo. Se discute el impacto de estos minerales en el suministro de agua y minerales a la planta.

Palabras clave: arcillas tipo 2:1, CIC, vertisol, heterogeneidad del suelo.

Resumo: As características físicas e químicas do solo desempenham um papel fundamental no crescimento e rendimento da vinha. Os solos do Sul do Uruguai apresentam um elevado teor de montmorilonite ou illite. As proporções destes minerais merecem especial atenção, uma vez que influenciam a estrutura do solo e as propriedades hídricas. O presente estudo foi realizado numa vinha de 1,1 ha desta região caracterizada por uma elevada heterogeneidade de vigor vegetal. O seu objetivo era determinar e mapear as propriedades físicas e químicas do solo e as suas relações com o vigor e rendimento das plantas. A capacidade de troca catiônica (CEC) e os teores de argila e matéria orgânica foram medidos em 84 locais dentro desta vinha para calcular os teores de montmorilonite e illite do solo. Além disso, o tipo e abundância de argilas foram corroborados pela análise difractométrica de raios X. Os teores de CEC e montmorillonite foram positivamente correlacionados com a vigor da vinha, expresso pelo Índice de Vegetação Normalizada (NDVI), diâmetro do tronco, peso da poda, área foliar, e com o rendimento. Assim, a distribuição dentro da vinha da razão montmorilonite/ilite condicionou a heterogeneidade do crescimento da vinha e o rendimento ao nível do campo. O impacto desses mineraisminerais na água e no fornecimento de minerais à planta é discutido.

Palavras-chave: argilas 2:1, CEC, vertisol, heterogeneidade do solo.

1. Introduction

Uruguay's viticultural history began with the arrival of the first Spanish and Portuguese immigrants during the colonial period. Currently, production extends over approximately 7,000 ha and generates about 30,000 direct and indirect jobs. Tannat is the emblematic Uruguayan variety due to its good performance in the country's soil and climatic conditions. The diversity of geological materials has generated very different soil types in Uruguay(1). In the south, these soils have developed on sediments. They are moderately deep (50 to 100 cm), clayey, and have a B horizon of illuvial character(2). The predominant soils are classified as fine,

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smectitic, thermic Verticargiudoll, with particular properties: high organic matter content and richness in expansive clays of type 2/1[3]. The temperate climate of Uruguay, with around 1100 mm rain per year, allows grapevine cultivation with high yield objectives.

The soil physical properties (texture, structure, depth, colour, and temperature) and chemical properties (pH, electrical conductivity and nutrient availability) are determinant for plant functioning[4][5], determining grape vigour and quality[5][6]. Thus, the soil variability can generate an heterogeneity of plant growth and functioning, as observed by vegetation imagery in some vineyards[7]. The non-uniformity of yield, berry composition and berry sanitary status can lead to technical, economic, and environmental issues[8][9][10][11]. It is then important to identify the soil factor(s) playing a key role(s) in vine heterogeneity to propose corrective management levers. The presence of montmorillonite and illite is a typical signature of the soils of South Uruguay[3], but the proportion of these two clay types is unknown and seems variable throughout the region. Variation at the field level seems to have escaped any investigation.

The objective of this short communication was to evaluate the relationship between the field heterogeneity of grapevine in terms of plant variables (vigour and yield) and the physical and chemical soil characteristics, including in particular the content of illite and montmorillonite. For such purpose, a vineyard displaying strong heterogeneity of plant vigour was used as a case study.

2. Materials and methods

2.1 Study site

The field of the study was a commercial vineyard of 1.1 ha planted in 1998 with *Vitis vinifera* L. cv. Tannat, grafted on SO4 rootstock. This vineyard is located in Canelones, Uruguay (34° 36 S, 56° 14 W), 56 km away from Montevideo. The vine spacing was 2.5×1.2 m (3333 vines ha^{-1}). The vineyard was on a gradual slope of 1-2% (north/south). Vines were cultivated using a double guyot system and trained to a vertical shoot position. The vineyard was not irrigated. An intercrop occupied the inter-row and was regularly cut (mixture of *Graminaceae* spp. and *Asteraceae* spp.). The vineyard was characterized by high variability of yield and berry composition. Crop vigour was assessed at veraison by the Normalized Difference Vegetation Index (NDVI), calculated using aerial images, as described in Ferrer and others[10]. The vines were geo-referenced using a GPS (Thales Navigation Inc., San Dimas, CA, USA).

2.2 Soil determinations and characteristics

The chemical and physical properties of the soil were determined. For this purpose, soil samples were taken within the vineyard following a grid layout (10.8×12.5 m), obtaining 84 sampling points. The depths of sampling were 0-20 cm and 20-40 cm. During winter 2015, organic matter (OM), the percentage of sand (Sa), clay (Cl), and silt (Si) were determined for the two depths, while cation exchange capacity (CEC) was determined for the 0-20 cm samples.

To identify and quantify the different clay fractions (CT), a mixed soil sample was taken at a depth of 20-30 cm for each vigour zone (High Vigour: HV, and Low Vigour: LV). The clay fractions were analysed by X-ray diffractometry (XRD), as described by Beaux and others[12] at the laboratory of the Department of Technological Development of CURE (http://www.cure.edu.uy/). The methodology for sample preparation and clay analysis was adapted from Carroll[13].

To determine the montmorillonite and illite contents in the soil, we have admitted that kaolinite was negligible[3], and we have considered that soil CEC is the sum of partial CEC (Eq. 1), and that the clay content is the sum of clay type contents (Eq. 2).

CEC of soil = CEC of OM + CEC of illite + CEC of montmorillonite (Eq. 1)

illite content + montmorillonite content = clay content (Eq. 2)

Considering 30 and 90 cmol+.kg^{-1} for CEC of illite and montmorillonite[14], and 250 cmol+.kg^{-1} for OM[15], the equation (Eq. 1) becomes:

30 illite content + 90 montmorillonite content = soil CEC – 250 OM content (Eq.1 bis)

The set of equations (Eq. 1 bis) and (Eq. 2) was solved for every point corresponding to a soil sample. The QGIS (Geographic Information System; 2021) program was used to draw maps of the trunk diameter, CEC, montmorillonite, illite and OM using TIN interpolation.

2.3 Plant growth and yield components

In winter 2020, trunk diameter (TD) was evaluated, following the same grid scheme used for soil analysis (n=84), by a digital caliper (Neiko 01407 ± 0.2 mm) at 10 cm above the grafting point following the methodology proposed by Santesteban and others[16]. For each plant, two measurements were taken, one transverse and one longitudinal to the row. The average of both measures was used as the average TD for that plant.

The influence of soil properties on plant response was addressed within two randomized blocks characterized by high vigour (HV) and low vigour (LV) with three replications for each of them. Each replication included 21 vines distributed in two rows (63 plants per treatment).The plant parameters were the following: Exposed leaf area (ELA, m^2/vine) assessed at veraison by the method proposed by Carbonneau[17], Yield (Y, kg/vine) measured at maturity, and Pruning weight (PW) measured during winter. Pearson's linear correlation between plant parameter and soil parameters, or between soil parameters were calculated. Soil parameters included the illite content, ill-30 [for illite at 30 cmol+ kg^{-1}] and montmorillonite content, mmt-90 [for montmorillonite at 90 cmol+ kg^{-1}] in the 0-20 cm layer, clay (Cl 0-20, Cl 20-40) and organic matter (OM 0-20, OM 20-40) in the two layers and CEC of the 0-20 cm layer.

3. Results

Three NDVI ranges were delimited within the vineyard, corresponding to high (NDVI 0.57 to 0.61)/ medium (NDVI 0.55 to 0.57)/low (NDVI 0.55 to 0.48) (Fig. 1, A). The vineyard's west part reached NDVI corresponding to the high vigour class (HV), while the NDVI on east part corresponded to the low vigour class (LV). Those zones were corroborated by the range of trunk diameter values (Fig. 1, B). The variation of the trunk diameter at plot level was 20% (CV) with a mean value of 49 mm (range: 30 to 66 mm).

The mean CEC decreased from HV to LV zones (Fig. 1, C), ranging from 24-35 cmol+ kg^{-1} in the HV zone and 14-23 cmol+ kg^{-1} in the LV zone. The spatial variation of CEC was similar to the one of NDVI, with higher CEC in the HV zone and lower CEC in the LV zone.

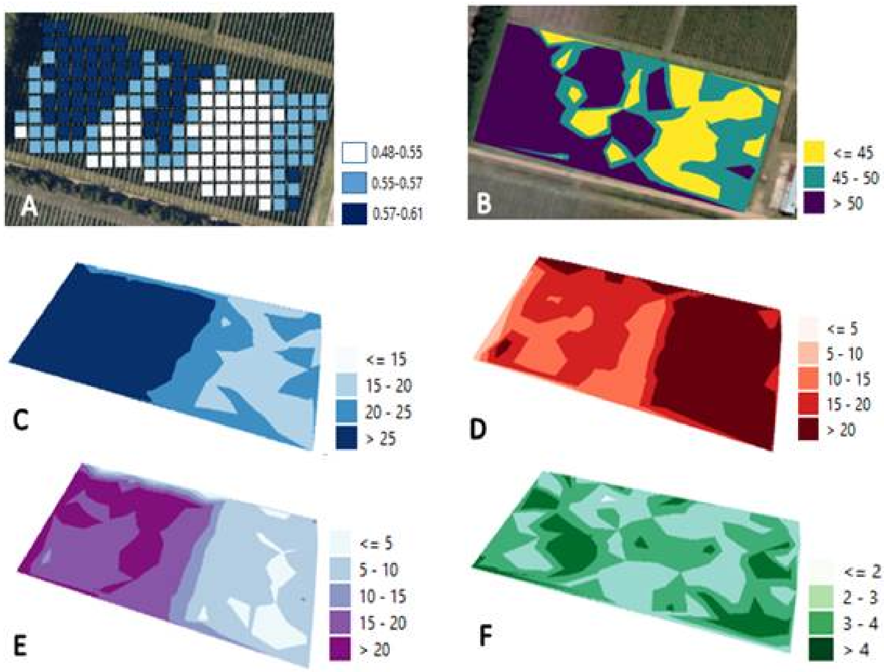

FIGURE 1
Vigour and soil properties maps. Vigour by NDVI (A); vigour by trunk diameter (ϕ in mm, B); CEC map (cmol+ kg-1, C); illite content (%, D); montmorillonite (%, E); organic matter (%, F). Soil maps in a depth of 0 to 20 cm. n=84

On average the content of illite (Fig. 1, D) was 18.8% (range 4.6 to 28.8%), while montmorillonite (Fig. 1, E) was 14.4% (range 3.7 to 26.7%).

Organic matter was on average 2.9% at 0-20 cm depth. Some areas presented higher OM content (Fig. 1, F) than others. These areas did not follow the patterns of NDVI map.

Mineralogical analysis of the clays showed differences in the abundance of 2:1 clays. The HV zone had 79% montmorillonite and 20% illite. In contrast, the LV zone reached 34% of montmorillonite and 60% of illite. Both soil zones had a low content of the 1:1 clay type kaolinite (between 1% for the HV zone and 6% for the LV zone).

The high vigour (HV) zone was characterized by higher yield and vegetative growth compared to the LV zone (Table 1). The most significant heterogeneity (CV) was found in low vigour for the four variables studied. ELA and PW were the variables with the greatest dispersion in the plot. As well, for these variables, the CV is particularly higher in low vigour zone compared to high vigour. Trunk diameter was correlated with the following plant variables: NDVI (r^2: 0.58; p-value: 0.05), ELA (r^2: 0.60; p-value: 0.05); Y (r^2: 0.69; p-value: 0.001) and PW (r^2: 0.63; p-value: 0.05).

TABLE 1
Plant variables mean values and variability according to the vigour zone

Vigour variables	High vigour		Low Vigour	
	Mean	CV (%)	Mean	CV (%)
Y	6.96*	17	5.11*	23
ELA	1.76*	19	1.2*	30
PW	0.57*	20	0.35*	27.8
TD	58*	17	36*	21

Y: Yield (kg/vine); ELA: Exposed Leaf Area (m^2/vine); PW: Pruning weight (kg/vine); TD: Trunk Diameter (mm).
The * indicate significant differences according to the Fisher test (p-value < 0.05). n=63 (Y, ELA and PW) n=84 (TD).

Correlations between plant and soil variables, or between soil variables, were analysed. NDVI correlated negatively with illite content and positively with montmorillonite content. The illite and montmorillonite contents also correlated with the TD, ELA, cane production and Y (Table 2). The correlations were negative for illite and positive for montmorillonite, with higher level of significance for montmorillonite. All the plant parameters also correlated positively with CEC. However, no correlation of plant parameters with organic matter was observed (except a negative one for TD).

The soil parameters showed little correlation except for the clay types. The organic matter in 0-20 cm correlated positively with illite but negatively with montmorillonite. This is concordant with the negative correlation of CEC and organic matter in 0-20 cm because montmorillonite has more weight in soil CEC than organic matter. Illite content (in 0-20 cm) correlated negatively with the clay content in 20-40 cm, while the opposite was true for montmorillonite. The montmorillonite content (in 0-20 cm) correlated positively with the clay content in 0-20 cm. Higher clay levels thus reflected higher montmorillonite levels in the two horizons.

4. Discussion

Based on the soil chemistry analyses and CEC, the soil in the site study is a VerticArgiudoll[2]. Differences in clay content and clay type between the two vigour zones can explain the differences in water retention in each vigour zone and the ones in plant growth and yield[4][5]. Indeed, soil water retention and nutrient availability (mainly nitrogen) impact the overall plant functioning[18]. Montmorillonite is a swelling clay[19]. The positive correlation of the soil's montmorillonite content with the vine's vegetative development is plausibly due to the weakening of the clay-humus association as the soil moisture varies[14]. The tips of the roots are thus facing aggregates with poor stability (“soft humus”). In places where illite is dominant over montmorillonite, the clay-humus association is in contrast more stable favouring a harder soil structure. Another factor is the high pluviometry in the region. Drought is relatively rare. The montmorillonite keeps its hydrated state so that the bulk density of the soil has lower values in areas where this type of clay predominates over illite.

TABLE 2
Coefficient of Pearson

Parameters		ill-30	mmt-90	Cl 0-20	Cl 20-40	OM 0-20	OM 20-40	CEC
Plant	NDVI	-0.34*	0.49***	0.29*	-0.07	-0.20	0.12	0.52***
	Yield	-0.46**	0.50***	0.49***	0.38*	-0.24	-0.15	0.59***
	ELA	-0.41**	0.43**	0.17	0.39*	-0.26	-0.01	0.49***
	TD	-0.57***	0.78***	0.25	0.22	-0.44**	0.06	0.68***
	CP	-0.52***	0.65***	0.30*	0.41**	-0.21	-0.05	0.68***
Soil	ill-30	1	-0.75***	-0.21	-0.52***	0.44**	0.06	-0.66***
	mmt-90		1	0.45**	0.36*	-0.41**	0.01	0.91***
	Cl 0-20			1	0.24	-0.15	-0.14	0.65***
	Cl 20-40				1	-0.16	-0.07	0.37*
	OM 0-20					1	-0.05	-0.46**
	OM 20-40						1	0.10
	CEC							1

Plant variables: NDVI: Normalized Difference Vegetation Index; ELA: Exposed Leaf Area; TD: Trunk Diameter; PW: Pruning weight. Soil parameters: ill-30: illite, mmt-90: montmorillonite, Cl0-20: Clay at 0-20cm, Cl20-40: Clay at 20-40cm, OM0-20, OM20-40: Organic matter at 0-20cm and 20-40cm; CEC: Cation Exchange Capacity. (*: p<0.05; **: p<0.01; ***: p<0.001).

Higher montmorillonite content or higher montmorillonite/illite ratio in the 0-20 cm horizon of the soil has thus favoured grapevine growth as reflected by the NDVI, leaf exposed area, pruning weight and trunk diameter, and ultimately has also favoured high yields.

The negative correlation between organic matter (in 0-20 cm) and montmorillonite could reflect the weaker association of this clay type with humus. As grapevine is a perennial crop, the roots could have experienced an improved growth in these areas because the root tips have encountered a weaker resistance to penetration. With CEC being higher in these zones (higher CEC of montmorillonite), the mineral nutrition should not have been a limiting factor compared to the zones where illite is the dominant type of clay. The negative correlation between illite content in 0-20 cm and clays in 20-40 cm is more difficult to explain. Clay type migrations during soil history could be one of the explanations.

High vigour has been associated with deeper soils[5][6][7][8][9][10][11][12][13][14][15][16][17][18][19][20], higher organic matter content[4], higher cation exchange capacity[5][6][7][8][9][10][11], % clay[5][6][7][8][9][10][11][12][13][14][15][16][17][18][19][20][21], higher water availability[15][16][17][18][19][20] and plant nitrogen availability[11][12][13][14][15][16][17][18][19][20][21][22]. These associations between soil and plant vigour are confirmed by our results (Table 1, Figure 1). The trunk diameter is an indicator of vine vigour, but, unlike the other plant variables addressed in the present study, it expresses vigour as a cumulative result over the plant's life[23]. The correlation between TD and other vigour variables (PW and Y) makes the trunk diameter an appropriate (and simple) indicator to characterize the heterogeneity of vigour. Also, differences in soil's physical and chemical properties were shown to be linked to spatial variations in trunk circumference as in other studies[24]. Similar to our results, Bramley and others[20] observed greater trunk circumference in grapevine with excessive vigour over years. Other plant variables such as pruning weight, vegetative growth and yield were also positively correlated with soil variables such as CEC and montmorillonite. These plant variables are used as vigour indicators over a short period (one year)[20]. We recently reported that those annual variables related to vigour also correlated with berry primary metabolism[25].

5. Conclusions

From our knowledge, no study of the within-field variation of CEC, illite, and montmorillonite has been reported. The main reason is plausibly that research has rarely investigated soil CEC at decametric granularity. Corroboration with mineralogical analysis of clays seems to support our assumptions. Although the number of samples for this analysis was very low (one for each vigour zone), the authors consider that it provides a good approximation of the relationship between plant vigour and clay types.

This study was carried out in a single vineyard and has a series of methodological limitations that prevent generalizing the information obtained. However, the authors consider that it provides new knowledge about the relationship between plant vigour and type of clays. It should be interesting to apply the same analysis to any vineyard growing in soils rich in 2/1 clays. In the future, deeper layers of the soil should be included in order to have a three-dimensional view of clay components variation.

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