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Effects of soil type on vineyard performance and berry composition in the Río de la Plata coast (Uruguay)

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Abstract

Aims: Vineyards in Uruguay are concentrated over soils formed from Quaternary sediments; however, in recent years vineyard surface over soils formed from metamorphic rocks has increased. In this context, this study assessed the relationships between soil physical properties and grapevine vegetative development, yield and berry composition, in order to understand how vine response is affected and characterize the viticultural production potential for different regions.

Methods and results: The work was conducted from 2011 to 2014 in non-irrigated Tannat commercial vineyards located in the Río de la Plata coastal region. Roots were studied by excavating trial pits and soils were described. For each vintage, the Dryness index was estimated and pre-dawn leaf water potential was measured. Vine response (vigor, yield and berry composition) was determined for each vineyard. Three soil texture classes over two types of parent rock were observed. Vineyards on soils formed over metamorphic rocks, coarse-textured and with lower depth and water availability, had lower yield, lower vegetative development and higher concentration of compounds associated with berry quality. In contrast, vineyards on soils formed over Quaternary sediments or over metamorphic rock but with greater water availability showed the inverse response.

Conclusion: The amount of available water in the root zone significantly affected plant growth, yield, bunch rot and berry composition.

Significance and impact of the study: According to edaphic conditions, it is possible to optimize grapevine production within the sub-region of Río de la Plata coast by balancing the source:sink ratio for each soil through vineyard management.

Key words: Soil-texture, available water potential, root zone, vine, berry composition, yield, Río de la Plata coast wine-growing area, Tannat

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Introduction

Soils are essential components of viticultural terroirs, along with climate, plant and human factors (Seguin, 1986; Deloire *et al*., 2005), influencing vineyard performance and berry and wine composition (Tisseyre *et al*., 2007; Trought *et al*., 2008; Van Leeuwen, 2010).

The volume of soil potentially explored by roots depends on its physical properties. Texture is widely used for soil characterization and as root-zone volume indicator (Oliver *et al*., 2013). In fact, soil depth and clay fraction exert a strong influence on grapevine development and yield (Bodin and Morlat, 2006; Trought *et al*., 2006), maybe because they determine water supply and aeration (Lanyon *et al*., 2004; Tardáguila *et al*., 2011). However, the apparent influence of soil properties on berry composition is indirect (Zerihun*et al*., 2015), being mediated by their effects on canopy size, which is negatively associated with berry quality. On shallow soils, grape soluble solids content and pH are higher and titratable acidity is lower (Trought *et al*., 2008). Moreover, soils with less water and organic matter lead to higher anthocyanin concentrations in grape skins (Cheng *et al*., 2014).

Usually, soils devoted to quality-grape production show lower yields (Van Leeuwen *et al*., 2008; Renouf *et al*., 2010). However, if yield is to be used as a management goal in viticulture, optimal yield ranges for different cultivars, soil types and climatic conditions need to be developed, and so soil quality must be monitored (Lanyon *et al*., 2004). This is justified by the fact that high yields can be obtained in soils with large ranges in coarse elements or clays (Seguin, 1986); therefore, it is not possible to define an ideal soil using texture only (Seguin, 1983).

According to Morlat *et al*., 1999), it is possible to estimate the terroir-induced vigor and precocity of the vines by considering soil depth, water availability, natural drainage, root depth and slope, among other factors. This approach has been validated by Bodin and Morlat, 2006) and Morlat and Bodin, 2006).

A number of studies have reported that the best grape quality is obtained under moderate water stress conditions during the maturation period (Matthews and Anderson, 1988; van Leeuwen and Seguin, 1994; Choné *et al*., 2001; Ojeda *et al*., 2002; Roby *et al*., 2004). The absence of water deficit in vines during ripening determines a low quality potential due to increased competition between reproductive and vegetative sinks, as well as disorders in secondary metabolism (Koundouras *et al*., 1999). Similarly, severe water stress has negative consequences for grape and wine quality (Morlat *et al*., 1992).

Soil characterization is time-consuming and costly. Recently, electromagnetic sensors have been used for assessing soil apparent electrical conductivity (ECa), making it possible to take a large number of measurements in a short time and to differentiate soil areas according to water availability (Sudduth *et al*., 2005; Goulet and Barbeau, 2006). ECa is strongly correlated with soil texture (Bramley *et al*., 2011; Rodríguez-Pérez *et al*., 2011) and has proven to be a reliable predictor of within-field spatial variability, since it is significantly correlated with plant growth and yield (Bramley *et al*., 2011; Rossi *et al*., 2013). This technique allows for a rapid soil characterization that would facilitate vineyard management decision making.

In Uruguay, the viticultural areas are concentrated on the coastline of the Río de la Plata, mainly in the southern and southwestern regions of the country, over soils formed from Quaternary sediments (QS). In the last decade, vineyard area has increased in eastern and other regions, over soils formed from metamorphic rocks (MR) (Celio, 2016).

In this context, the current study, conducted across four vintages, aimed to relate grapevine vegetative development, yield, and berry composition with soil texture classes and water contents in order to characterize the viticultural potential of soils from six regions along the Río de la Plata coast of Uruguay.

Materials and Methods

1. Location of the studied sites

Nine plots distributed over 300 km along the Uruguayan coast of Río de la Plata, on different types of soils and geological parent materials, were selected for the current study. The plots are numbered 1 to 9 from west to east, with plots 1 and 2 in Colonia del Sacramento (Colonia Department) and plots 8 and 9 in Laguna del Sauce and Pueblo Edén (Maldonado Department) (Supplementary Figure 1). This region is characterized by high annual rainfall. According to the Instituto Nacional de Meteorología of Uruguay (http://www.meteorologia.com.uy/ServCli/tablasEsta disticas), accumulated rainfall over the growing season (September 1st to March 31st) is 721 mm in the west, 662 mm in the central region, and 645 mm in the east of the Uruguyan coast of Río de la Plata. The accumulated monthly average is 103±17 mm in the west, 95±10 mm in the central region, and 92±16 mm in the east.

2. Description of the experimental plots

The study was conducted from 2011 to 2014 in nine commercial, non-irrigated vineyards, where experimental plots were defined. In each plot, 30 Tannat (*Vitis vinifera* L.) vines from three rows with ten vines each were randomly selected. Plants were trellised to Vertical Shoot Positioning and pruned using a Guyot system; rows were oriented north-south in all sites. Location, rootstock, year of plantation and vine spacing are reported in Table 1.

3. Vine vigor measurements

Exposed leaf surface (SFEp) was estimated at veraison as proposed by Carbonneau, 1995. At harvest, one shoot with clusters was collected from 10 vines, and leaves, clusters and wood were separated. Fresh weight per organ was measured, as well as shoot length. Then, samples were dried at 50°C in an oven and expressed as dry weight per plant organ. Dry weight per linear meter was estimated using the average number of shoots per linear meter from all the vines in the plot and the average dry weight of 10 shoots. A relative indicator of vigor was expressed as dry weight per cm of shoot.

4. Root characterization

Roots were studied by excavating trial pits in the row from soil surface to the parent material. The amount, diameter and distribution of roots were determined at different distances from the vine axis and in parallel to the row. Roots were painted, photographed, mapped over a 100-cm^2 grid, and classified according to their diameter as < 3 mm, 3 to 5 mm, and > 5 mm.

Root depth was defined as that where 90% of active roots (diameter < 3 mm) could be found. This depth was used for estimating Dryness index (DI) and soil textural class for the root zone (TCra).

5. Soil characterization

The soil of each plot was described according to FAO (2006) guidelines and classified following USDA Soil Taxonomy (Soil Survey Staff, 1999). Two samples were taken from each horizon in the excavated trial pits for physical and chemical analysis. Moreover, at least five more samples were collected on each plot using a manual drill to complement the observations of structure, texture, depth and presence of active roots.

Soil texture was determined by the method of Bouyoucos (1962) and soil organic carbon (SOC) by that of Walkley and Black (1934). The relative clay, sand and silt contents were calculated in all horizons down to the active-root depth, thereby assigning a new TCra.

During the 2012-2013 growing cycle, soil ECa was measured in the inter-row with an EM38 electromagnetic equipment (EM38-Geonics, Mississauga, Ontario, Canada), using the vertical

Table 1. Characteristics of the studied vineyards.

Plot	Location	Site	Rootstock	Year of plantation	Spacing
1	34° 23' 47,40" S; 57° 52' 49,67" W	Real de Vera	3309C	2000	2.50m x 1.20m
2	34° 23' 17,40" S; 57° 51' 07,37" W	Piedra de los Indios	3309C	1999	2.50m x 1.15m
3	34° 07' 10,46" S; 56° 56' 50,98" W	Mal Abrigo	3309C	2000	2.00m x 0.90m
4	34° 36' 44,77" S; 56° 14' 42,02" W	Juanicó	SO4	1998	2.50m x 1.10m
5	34° 53' 04,55" S; 56° 19' 24,33" W	Punta de Yeguas	3309C	2005	2.50m x 1.00m
6	34° 39' 30,43" S; 55° 47' 56,11" W	Atlántida A	3309C	2006	2.50m x 0.90m
7	34° 39' 36,70" S; 55° 47' 55,22" W	Atlántida B	3309C	2006	2.50m x 1.00m
8	34° 42' 31,74"; 55° 03' 31,56" W	Sierra Ballena	Gravesac	2004	2.50m x 1.00m
9	34° 44' 36,22" S; 55° 01' 16,42" W	Pueblo Edén	101-14Mg	2005	2.50m x 1.20m

dipole, taking at least one measurement every 7 plants. These measurements were performed on the same dates as pre-dawn leaf water potential readings.

The DI was used to determine the available soil water and was calculated according to Riou and Lebon (2000), as adapted by Ferrer *et al*. (2007). The DI was estimated from September to harvest. The available water capacity (AWC) within the soil profile occupied by roots was estimated following the method proposed by Fernández (1979). This measure was considered the starting point in the water balance analysis.

6. Leaf water potential

Pre-dawn leaf water potential (LWPpd) was determined with a pressure chamber (Soil moisture equipment, Santa Barbara, CA, USA). Measurements were made before dawn in 20 adult, healthy leaves per plot at four different stages of grapevine development: fruit-set, veraison, pre-harvest and harvest.

7. Yield components and bunch rot incidence

At harvest, the yield of the 30 plants per plot was individually weighed, the number of clusters was counted and the average weight per bunch was calculated by dividing yield per vine by the number of clusters. Rot incidence was estimated by weighing bunches with at least 5% of berries affected and was expressed as percentage of total yield per vine. Berry weight was measured in samples of 250 randomly collected berries.

8. Grape samples and analysis

Harvest was carried out at "technological maturity" for each plot. The criteria for determining the harvest date were: maximal sugar content (g/L), total acidity (g H_2SO_4) between 4.0 and 5.5, pH between 3.2 and 3.5, and onset of berry weight decrease; the appearance of characteristic symptoms of bunch rot and/or pH greater than 3.5 prevailed over other parameters. These parameters were analyzed periodically according to OIV (2009) methods. For this purpose, replicated 250-berry samples from all vines in each plot were collected weekly from veraison to harvest. Berry composition was determined after manually destemming the berries and obtaining the juice by crushing the pulp with an electric blender (HR2290, Phillips, The Netherlands). Soluble solids contents (SS) were measured using a refractometer (Atago N1, Atago, Tokyo, Japan); pH was determined with a pH meter (HI8521, Hanna Instruments, Villafranca Padovana, Italy); and total acidity (TA) was measured by titration and expressed as g sulfuric acid/L juice.

Total anthocyanins (ApH1), extractable anthocyanins (ApH 3.2), phenolic richness (A280) and cell maturity index (EA) were determined in the grape samples according to Glories and Augustin (1993). All the measurements were carried out in duplicate with a Shimadzu UV-1240 Mini spectrophotometer (Shimadzu, Japan), using glass (for anthocyanins) and quartz (for absorbance at 280 nm) cells with 1-cm path length. The indexes were calculated considering the respective dilution of the grape extracts, according to González-Neves *et al*. (2004).

9. Statistical analysis

Multivariate techniques, such as Principal Component Analysis (PCA) and Hierarchical Clustering (HC), were used to determine the relationships between vine variables (vigor, yield and berry composition) and soil classes. Variables were standardized by vintage year, as follows:

$$SV_x = \frac{V_x - \bar{V}}{SD_V}$$

where V_x is the value of the original variable at position x (mean by plot and year), and V and SD_v are, respectively, the average and the standard deviation of the original variable by vintage year.

Plant response to TCra was analyzed by MANOVA and means were separated using the LSD Fisher test ($p<0.10$). Discriminant analysis was used to characterize the relationships between soil (depth, AWC, ECa, DI) and vine (LWPpd) water-related variables and soil profile (textural class and geological material). Moreover, Pearson's correlation coefficient was employed to assess significant relationships among variables. All statistical analyses were carried out using the Info Stat software.

Results

According to USDA classification, three soil groups were identified on the studied vineyards (Table 2), and they belonged to three textural classes: silty clay loam, silty clay, and clay loam. Parent materials were either QS or MS ("average degree" and "quaternary sediments"). In plot 9, the presence of limestone over the MR justified the sub-classification. Great differences among sites were observed for root zone depth, varying from 36 to 70 cm, with soils formed over MR being the shallowest. Depth, soil textural class and SOC determine AWC, which ranged from 57 to 123 mm. According to the monthly rainfall

Table 2. Main soil characteristics for each plot.

Plot	Geology (parent rock)	USDA soil classification	Depth* (cm)	AWC* (mm)	Textural class* (TCra)
1	Quaternary sediments (QS)	Typic Argiudoll	50	96	Silty clay loam
2	Quaternary sediments (QS)	Typic Argiudoll	56	97	Silty clay loam
3	Metamorphic rock average degree (MRad)	Typic Hapludoll	36	76	Clay loam
4	Quaternary sediments (QS)	Vertic Argiudoll	70	123	Silty clay
5	Quaternary sediments (QS)	Typic Argiudoll	60	110	Silty clay
6	Metamorphic rock (MR)	Typic Hapludert	43	67	Clay loam
7	Metamorphic rock (MR)	Abruptic Argiudoll	36	57	Clay loam
8	Metamorphic rock (MR)	Lithic Hapludoll	36	68	Clay loam
9	Metamorphic rock and Quaternary sediments (MR/QS)	Abruptic Argiudoll	54	85	Clay loam

*Depth with 90% of visible roots with a diameter < 3 mm

Table 3. Vine response according to soil textural classes (means ± standard deviations).

Plot	Geology (parent rock)	USDA soil classification	Depth* (cm)	AWC* (mm)	Textural class* (TCra)
1	Quaternary sediments (QS)	Typic Argiudoll	50	96	Silty clay loam
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4	Quaternary sediments (QS)	Vertic Argiudoll	70	123	Silty clay
5	Quaternary sediments (QS)	Typic Argiudoll	60	110	Silty clay
6	Metamorphic rock (MR)	Typic Hapludert	43	67	Clay loam
7	Metamorphic rock (MR)	Abruptic Argiudoll	36	57	Clay loam
8	Metamorphic rock (MR)	Lithic Hapludoll	36	68	Clay loam
9	Metamorphic rock and Quaternary sediments (MR/QS)	Abruptic Argiudoll	54	85	Clay loam

*EMG = malvidin-3-glucoside equivalent.
Values on each row followed by different letters are significantly different according to Fisher's LSD test ($p \leq 0.10$).

regime in the region (96.7 mm per month), soils would be at field capacity in the springtime.

Significant differences in vine vigor were detected among soil TCra classes (Table 3). Clay loam soils showed lower SFEp values, whereas shoot length was lower under silty clay loam soils. No significant differences among soil classes were detected for total shoot and linear dry weights. However, vines grown on clay loam soils presented the highest dry weight per cm of shoot. In summary, biomass production was lower in clay loam soils.

Yield components showed significant differences among soil classes (Table 3), except for berry weight. Vines on clay loam soils showed lower yield, bunch dry weight and rot incidence, whereas vines on silty clay soils showed the highest yield and bunch rot incidence.

Berry composition was mainly unaffected by soil textural class, except for phenolic and anthocyanin concentrations (Table 3). Vineyards on clay loam soils produced berries with the highest concentrations in total and extractable anthocyanins and phenolic compounds, whereas the lowest values were observed for berries from vineyards on silty clay soils. No significant differences were detected for SS, TA, pH and EA.

Vine variables (vigor, yield components, sanitary status and berry composition) were separated according to plot and soil TCra classes by PCA (Figure 1). Principal component (PC) 1 explained 37.6% of the variance and PC2 explained 17.1%, together explaining 54.7% of the total variance in the dataset.

Those traits associated to berry quality (SS, EA, ApH1, ApH3.2 and A280) were located on the negative side of PC1, close to plots 6, 7 and 8, with clay loam soils. In addition, plot 9 (clay loam soils) was associated to berry quality, although with higher

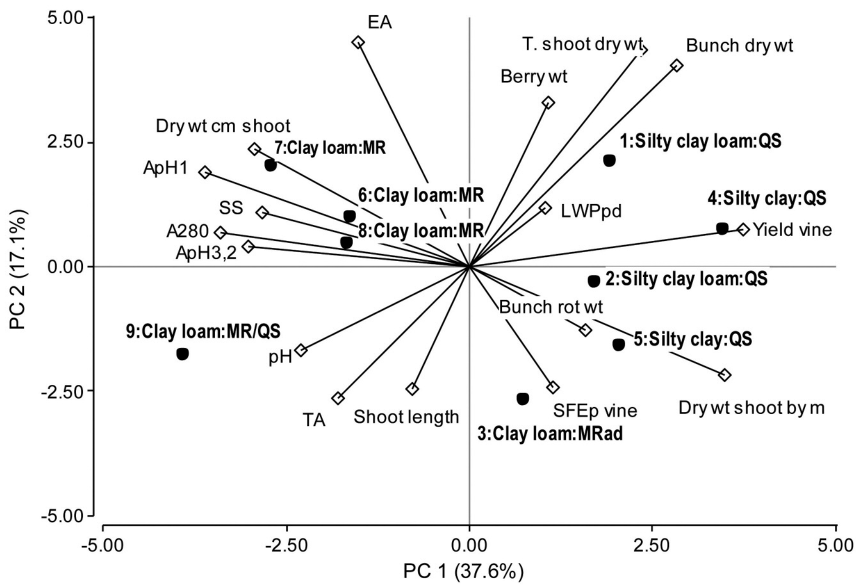

Figure 1. PCA of vine vigor, yield component and berry composition variables at harvest, as a function of plot, textural class in the active root zone (TCra) and geology. Variables were standardized per vintage year.

pH values and lower yields than the former plots. Plot 3, also on clay loam soils, was not related to quality attributes but to vigor variables.

Yield components were located close to plots 4 and 5, on silty clay soils, and plots 1 and 2, on silty clay loam, on the positive side of PC1. This group of plots was associated to less negative LWPpd values.

In contrast, biomass production (dry weight of shoot per linear meter, total shoot dry weight, bunch dry weight and SFEp per vine) had a more heterogeneous distribution. Shoot length, SFEp per vine and dry weight of shoot per m were located close to plots 5 (silty clay) and 3 (clay loam), on the negative side of PC2. In contrast, total shoot dry weight and yield components (berry weight and bunch dry weight) were located on the positive side of PC2. Berry composition variables were negatively correlated with yield and vigor, except for shoot length and dry weight per cm of shoot.

In addition, a negative correlation between SFEp per vine and EA was observed. A positive correlation between dry weight per cm of shoot and anthocyanins, and a negative correlation with bunch rot weight were also shown by PCA. Moreover, a negative correlation between dry weight of shoot per m and berry sugar and phenolic concentrations was also detected. Berry pH showed a negative correlation with yield components.

The LWPpd measured between veraison and harvest showed less negative values for vines over silty clay and silty clay loam soils and more negative values for those grown on clay loam soils. The LWPpd was negatively correlated with TA.

The parent rock of each plot revealed a relationship between quality attributes and yield over MR, whereas vigor and yield were related to QS. The sub-classes established for MR, such as MRad and MR/QS, showed an intermediate behavior.

When performed on the vine vigor variables, HC grouped together plots 6, 7 and 9 (clay loam soils), plots 1 and 2 (silty clay loam soils) and plots 4, 8, 5 and 3 (silty clay and clay soils) (Figure 2A).

When using yield components, HC grouped plots according to soil parent material (Figure 2B). As an example, plots 3, 7 and 8 had the highest coarse particle content in the soil profile and MR rock at low depth, whereas plot 6 had the same parent material but at greater depth.

For berry composition, HC gathered the plots in two groups (Figure 2C). The first group includes plots 6, 7, 8 and 9 (clay loam soils) and the second group includes plots 4, 5 (silty clay soils), 1, 2 (silty clay loam soils) and 3 (clay loam soils).

The relationship between TCra and those soil properties related with water availability for plants (ECa, depth, AWC, DI and LWPpd) was studied over the 2013 growing cycle. Discriminant analysis (Figure 3A) showed that most of the variability among plots was distributed along the first canonical axis. Clay loam and silty clay soils were clearly separated by the prediction ellipses, whereas silty

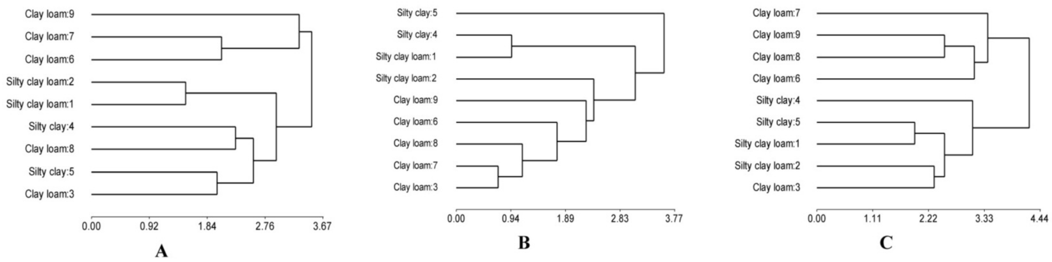

Figure 2. Ascending hierarchical classification (Euclidian mean) grouping plots and soil textural classes (TCra) based on similarity in vine vigor (A), yield components (B) and berry composition (C).

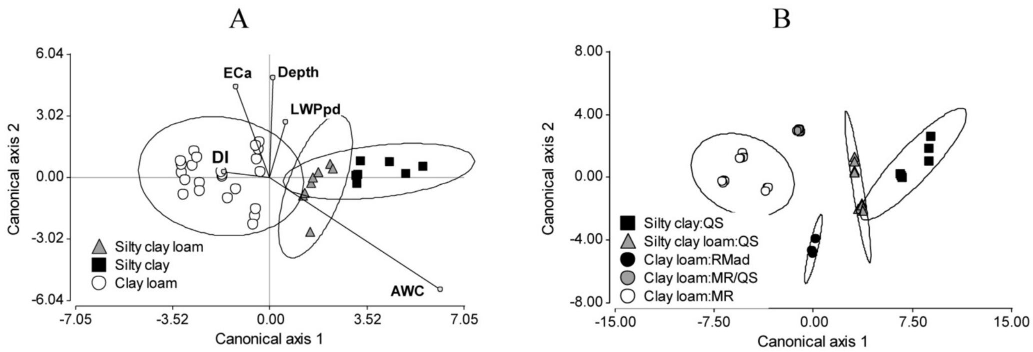

Figure 3. Discriminant analysis and prediction ellipses of measurements of soil apparent electrical conductivity (ECa), pre-dawn leaf water potential (LWPpd), soil available water capacity (AWC) and Dryness index (DI) in the nine studied plots. A- As per soil class (TCra) and B- As per soil class (TCra) and geology. Data correspond to the growing cycle of 2013.

clay loam soils appeared to have a behavior similar to that of the silty clay soils. The most important variable for this separation was AWC. When parent material was included in the analysis (Figure 3B), five independent groups were observed, except for a slight interception area between the ellipses for silty clay/QS and silty clay loam/QS soils.

Pearson correlation coefficients (Supplementary Table 1) for the aforementioned variables proved a strong correlation between depth and AWC, suggesting that soil depth is a determinant factor of soil water availability. A significant correlation was also observed between AWC and DI ($r=0.44$, $p<0.05$). Moreover, a high correlation was observed between ECa and depth ($r=0.83$, $p<0.001$) and ECa and AWC ($r=0.81$, $p<0.001$). A lower correlation coefficient was observed between ECa and DI ($r=0.37$, $p<0.05$). Finally, LWPpd measurements were not significantly related to any of the soil water availability variables studied.

Significant correlations between AWC and vigor, yield and berry composition variables for the growing seasons 2011-2014 were observed. Significant positive correlations were detected between AWC and SFEp per vine ($r=0.53$, $p<0.001$), yield per vine ($r=0.70$, $p<0.001$) and bunch rot weight ($r=0.47$, $p<0.05$), whereas negative correlations were found for AWC and dry weight per shoot ($r=-0.51$, $p<0.05$), SS ($r=-0.33$, $p<0.1$), pH ($r=-0.38$, $p<0.05$), ApH1 ($r=-0.43$, $p<0.05$) and A280 ($r=-0.43$, $p<0.05$). The other correlations with AWC had $r<0.3$ or $p>0.1$.

Discussion

In this study, the potential for viticultural production of soils from six regions along the coast of Río de la Plata was characterized for the first time. As reported by a number of authors (Tisseyre *et al.*, 2007; Trought *et al.*, 2008; van Leeuwen, 2010), the influence of soil on vegetative expression, yield, berry composition and vine sanitary status was verified. Soil physical properties and root zone depth were highly correlated with vine performance, as previously indicated by Bodin and Morlat (2006), Trought *et al.* (2006) and Oliver *et al.* (2013).

Apart from texture, soil structure plays a relevant role in vineyard performance. In some plots with high fine particule contents, roots were not able to explore deep soil layers. The presence of Bt horizons with high clay contents limited root development at greater depths due to physical limitations and lack of oxygen. Nevertheless, Typic and Vertic Argiudoll soils associated with QS showed greater root zone depths than Hapludoll, Hapludert and Abruptic Argiudoll soils when they are formed from MR (MR or MRad). In fact, our results showed that the presence of a silty layer between the soil and MR in the Abruptic Argiudoll soil from plot 9 created deeper soils.

Independently of the assigned textural class (TCra) and parent material, all vineyards except plot 1 had a Bt horizon with more than 40% clay (data not shown). This is a common and distinctive characteristic of the soils in this region.

In accordance with the reports of Van Leeuwen *et al*., (2008) and Renouf *et al*. (2010), a negative correlation was observed between two groups of variables: one group related to berry quality and the other related to vigor and yield. Even though the concentration and the evolution of compounds derived from the primary metabolism (SS, TA and pH) is part of the criteria used for deciding harvest date, similar results between different regions were obtained on the same season; however, they did not reflect the velocity in the accumulation of these compounds. Moreover, when the comparison of these variables accounted for the year effect, as expressed by the averages and standard deviations as a function of soil class in the ANOVA, differences were not significant. In contrast, secondary metabolites were different among soil classes, even when including the year effect.

Vines grown on deep soils formed on QS and classified as silty clay or silty clay loam showed greater vegetative expression than those grown on clay loam soils on MR. ANOVA results for vigor variables confirmed this trend, even though no significant differences were detected for total shoot dry weight and total linear dry weight. The HC analysis for vigor variables grouped the plots according to TCra, except for plots 3 and 8, which belonged to the clay loam class and were classified with other plots on silty clay soils because of their high dry weight per cm of shoot and shoot length. It is possible that in those plots, the relative importance of SFEp would be small due to a larger distance between shoots, which might promote an increase in shoot diameter and length without significantly increasing leaf surface. Nevertheless, the different analyses performed did not provide contradictory results, thus an association among soil physical properties and the potential for biomass production can be established, according to the model proposed by Morlat *et al*. (1999), Bodin and Morlat (2006) and Morlat and Bodin (2006).

Silty clay and silty clay loam soils, deeper and lighter textured, determined higher values for yield components. According to Wang *et al*., 2001), the size of the root system has a positive effect on shoot growth and, consequently, on yield per vine and berry and bunch dry weights.

HC for yield components showed plots ordered by geological material and TCra almost perfectly, from AWC, to plot 5 with a high AWC to plot 7 with the lowest AWC. In summary, yield components were greater on soils over QS, with lighter texture and higher AWC, as previously reported by Lanyon *et al*., 2004) and Tardáguila *et al*., 2011). In fact, yield from vineyards on clay loam soils was 35.4% and 40.1% that of vineyards on silty clay and silty clay loam soils, respectively.

Better results for berry quality traits were obtained under shallow soils with coarse texture. Bunch sanitary status and the concentrations of total and extractable anthocyanins, tannins and soluble solids were higher in vineyards grown on these soils. According to the Morlat *et al*. (1999) approach, soil properties in plots 3, 6, 7, 8 and 9 would generate a moderate water stress during maturation, thus favoring berry quality (Matthews and Anderson, 1988; van Leeuwen and Seguin, 1994; Choné *et al*., 2001; Ojeda *et al*., 2002; Roby *et al*., 2004; Mirás-Avalos *et al*., 2013). However, the weak correlation between LWPpd at maturation and some berry traits such as SS and TA identified by PCA proves that vine water status at maturation is not enough for explaining the plant qualitative response to water availability. In fact, when LWPpd measurements were initiated, vines had already attained the maximum vegetative development for the season. Therefore, in case no cultural practices (defoliation, cluster thinning) are performed, the source:sink ratio would be determined at veraison, as well as yield potential and the synthesis of berry compounds. The modulation of this potential would be dependent on the severity of the water stress at maturation, determined by DI, other environmental conditions (such as solar irradiation) and management practices (e.g. plant architecture). This implies interactions within the production system and assigns a negative correlation between vigor and berry composition, as expressed by Zerihun *et al*. (2015). Similarly to the results from the discriminant analysis, HC gathered plots in two groups as a function of berry composition attributes, depending on TCra and parent material. As in the former cases, plot 3 (clay loam and MRad) was included into the group of deep soils with light textures developed on QS. The hypotheses for explaining this behavior would be that: i) the higher AWC in relation to plots 6, 7 and 8 (also classified as clay loam) causes less water stress, thus affecting berry composition; and ii) since this soil presented a complex structure, and due to plant age, a second level of roots within the sub-soil may exist, allowing the vines to take water from this sub-soil when fine roots from upper layers would have limited ability to do so. The latter hypothesis represents an additional buffer capacity, as mentioned by Hunter *et al*. (2010).

Another possible factor is the percentage of soil organic matter (SOM; data not shown) because of its negative correlation with the synthesis of ApH1 (r=-0.34; p=0.08) and ApH3.2 (r=-0.37; p=0.06). SOM depends on soil type and its management. In the root zone, the lowest SOM values were detected in plots 6, 7, 8 and 9 (clay loam), then plots 1 and 2 (silty clay loam) and plots 4 and 5 (silty clay), as expected. However, plot 3 (clay loam) on MR showed the highest SOM, even higher than that of soils formed on QS. This fact is justified by the conversion of natural prairies for grazing to vineyards. The high SOM levels explain the high AWC of plot 3 (the proportion of SOM is used for its estimation), the high vigor (SFEp, vine and shoot length) and, as a consequence, the lower berry quality. With a normal precipitation regime during springtime, plot 3 would not present water deficits during this stage, which, in combination with N abundance, would favor vigorous canopy and root development.

As suggested by Cheng *et al*. (2014), plots 6, 7 and 8, with less water and organic matter, were related to the highest anthocyanin concentrations in grape skins. Soil conditions in these plots would create a balance in the vines biased to sinks (low Ravaz index) causing shoots with greater diameter and longer internodes, thus reducing yield and increasing the concentration of quality traits in the berries.

Sanitary problems observed in vineyards grown on silty clay soils would be associated to the greater vine vigor, which is related to vine microclimate and increasing humidity within the canopy (Ferrer *et al*., 2011).

Soil depth is the main factor determining AWC (r=0.93), along with texture and SOC. The measurements of ECa were strongly correlated with AWC, as pointed out by Sudduth *et al*. (2005) and Goulet and Barbeau (2006), and proved to be a reliable predictor of within-field spatial variability of AWC, which significantly affected plant growth and yield (Bramley *et al*., 2011; Rossi *et al*., 2013).

From the perspective of a given yield level allowing the expression of the terroir and the economic sustainability of the wineries, optimal source:sink ratios should be defined for each soil in order to maximize yield without compromising berry quality.

Conclusions

The current study proved that soil water availability is variable and depends on depth and texture, which are correlated with soil geological origin. Deep, light-textured soils formed over QS induced greater vegetative growth, higher yields and more sanitary problems. In contrast, coarse-textured soils formed over MR favored the production of better quality musts. Moreover, this study proved the need for further investigation on soil fertility since this is linked to physical conditions and soil use history. According to edaphic conditions, it was possible to define the viticultural interest of different areas within the sub-regions of Río de la Plata coast. From the central region to the west, on a 40-km long strip of coastline, it is possible to achieve high yields, whereas to the east, lower yields but better quality are expected.

References

Bodin F. and Morlat R., 2006. Characterization of viticultural terroirs using a simple field model based on soil depth - I. Validation of the water supply regime, phenology and vine vigour, in the Anjou vineyard (France). *Plant and Soil*, 281(1), 37-54. doi:10.1007/s11104-005-3768-0

Bouyoucos G.J., 1962. Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal*, 54(5), 464-465. doi:10.2134/agronj1962.00021962005400050028x

Bramley R.G.V., Ouzman J. and Boss P.K., 2011. Variation in vine vigour, grape yield and vineyard soils and topography as indicators of variation in the chemical composition of grapes, wine and wine sensory attributes. *Australian Journal of Grape and Wine Research*, 17(2), 217-229. doi:10.1111/j.1755-0238.2011.00136.x

Carbonneau A., 1995. La surface foliaire exposée potentielle. Guide pour sa mesure. *Le Progrès Agricole et Viticole*, 112(2), 204-212.

Celio A., 2016. Geología y vino: caracterización mediante elementos traza e isotopos estables de posibles terroirs ubicados sobre diferentes unidades geológicas de Uruguay. Tesis de Maestría. Montevideo - Uruguay, Facultad de Ciencias, Universidad de la República.

Cheng G., He Y.N., Yue T.X., Wang J. and Zhang Z. W., 2014. Effects of climatic conditions and soil properties on Cabernet sauvignon berry growth and anthocyanin profiles. *Molecules*, 19(9), 13683-13703. doi:10.3390/molecules190913683

Choné X., Van Leeuwen C., Chery P. and Ribereau-Gayon P., 2001. Terroir influence on water status and nitrogen status of non-irrigated Cabernet Sauvignon (*Vitis vinifera*.Vegetative development, must and wine composition (example of a Medoc top estate vineyard, Saint Julien area, Bordeaux, 1997.*South African Journal of Enology and Viticulture*, 22(1), 8-15.

Deloire A., Vaudour E., Carey V., Bonnardot V., and Van Leeuwen C., 2005. Grapevine responses to terroir: a global approach. *Journal International des Sciences de la Vigne et du Vin*, 39(4), 149-162. doi:org/10.20870/oeno-one.2005.39.4.888

FAO, 2006. *Guidelines for soil description*. 4th ed. Rome.

Fernández C.J., 1979. Estimaciones de la densidad aparente, retención de agua disponible en el suelo a partir de la composición granulométrica y porcentaje de materia orgánica. In *Reunión técnica de la Facultad de Agronomía*, 2, Anais Universidad de la República, Montevideo.

Ferrer M., Pedocchi R., Michelazzo M., González Neves G. and Carbonneau A., 2007. Delimitación y descripción de regiones vitícolas del Uruguay en base al método de clasificación climática multicriterio utilizando índices bioclimáticos adaptados a las condiciones del cultivo. *Agrociencia*, 11(1), 47-56.

Ferrer M., González-Neves G., Camussi G., Echeverria G. and Carbonneau A., 2011. Variety, plant architecture and pruning methods: influence on grey mould of grapevine. *Le Progrès Agricole et Viticole*, 128(18), 367-371.

Glories Y. and Augustin M., 1993. Maturité phénolique du raisin, conséquences technologiques : application aux millésimes 1991 et 1992, pp 56-61. In *Actes du Colloque Journée Technique du CIVB*, Bordeaux.

González-Neves G., Charamelo D., Balado J., Barreiro L., Bochicchio R., Gatto G., Gil G., Tessore A., Carbonneau A. and Moutounet M., 2004. Phenolic potential of Tannat, Cabernet-Sauvignon and Merlot grapes and their correspondence with wine composition. *Analytica Chimica Acta*, 513(1), 191-196. https://doi.org/10.1016/j.aca.2003.11.042

Goulet E. and Barbeau G., 2006. Contribution of soil electric resistivity measurements to the studies on soil/grapevine water relations. [Apports des mesures de résistivité électrique du sol dans les études sur le fonctionnement hydrique du système sol/vigne]. *Journal International des Sciences de la Vigne et du Vin*, 40(2), 57-69. doi:org/10.20870/oeno-one.2006.40.2.875

Hunter J.J., Archer E. and Volschenk C.G., 2010. Vineyard management for environment valorisation, pp 7-15. In *Proceedings of the VIIIth International Terroir Congress*, Soave, Italy.

Koundouras S., Van Leeuwen C., Seguin G. and Glories Y., 1999. Influence of water status on vine vegetative growth, berry ripening and wine characteristics in mediterranean zone (example of Nemea, Greece, variety saint-george, 1997). [Influence de l'alimentation en eau sur la croissance de la vigne, la maturation des raisins et les caractéristiques des vins en zone méditerranéenne (exemple de Némée, Grèce, cépage Saint-Georges, 1997)]. *Journal International des Sciences de la Vigne et du Vin*, 33(4), 149-160. doi:org/10.20870/oeno-one.1999.33.4.1020

Lanyon D.M., Cass A. and Hansen D., 2004. *The effect of soil properties on vine performance*. CSIRO Land and Water Technical Report 34/04, Glen Osmond, Australia. doi:org/10.4225/08/586be7e218029

Matthews M.A. and Anderson M.M., 1988. Fruit ripening in *Vitis vinifera* L.: responses to seasonal water deficits. *American Journal of Enology and Viticulture*, 39(4), 313-320.

Mirás-Avalos J.M., Trigo Córdoba E., Bouzas Cid Y., Díaz Losada E. and Orriols Fernández I., 2013. Relación entre humedad del suelo y estado hídrico de albariño bajo condiciones de riego y secano. *Estudios en la Zona No Saturada del Suelo* vol. XI, 85-90.

Morlat R. and Bodin F., 2006. Characterization of viticultural terroirs using a simple field model based on soil depth - II. Validation of the grape yield and berry quality in the Anjou vineyard (France). *Plant and Soil*, 281(1), 55-69. doi:10.1007/s11104-005-3769-z

Morlat R., Penavayre M., Jacquet A., Asselin C. and Lemaitre C., 1992. Influence des terroirs sur le fonctionnement hydrique et la photosynthèse de la vigne en millésime exceptionnellement sec, 1990). Conséquence sur la maturation du raisin. *Journal International des Sciences de la Vigne et du Vin*, 26(4), 197-220. doi:org/10.20870/oeno-one.1992.26.4.1190

Morlat R., Guilbault P. and Rioux D., 1999. *Une méthode opérationnelle d'étude des terroirs viticoles et de leurs effets sur la vigne et le vin: optimisation et valorisation par la viticulture. Application au vignoble de l'Anjou (Val de Loire, France)*. Rapport méthodologique de fin de contrat du programme Terroirs d'Anjou, 1994-1999).

OIV, 2009. *International oenological codex*. Organisation Internationale de la Vigne et du Vin. Paris: OIV.

Ojeda H., Andary C., Kraeva E., Carbonneau A. and Deloire A., 2002. Influence of pre- and postveraison water deficit on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. shiraz. *American Journal of Enology and Viticulture*, 53(4), 261-267.

Oliver D.P., Bramley R.G.V., Riches D., Porter I. and Edwards J., 2013. Review: soil physical and chemical properties as indicators of soil quality in Australian viticulture. *Australian Journal of Grape and Wine Research*, 19(2), 129-139. doi:10.1111/ajgw.12016

Renouf V., Tregoat O., Roby J.P. and Van Leeuwen C., 2010. Soils, rootstocks and grapevine varieties in prestigious Bordeaux vineyards and their impact on yield and quality. *Journal International des Sciences de la Vigne et du Vin*, 44 (3), 127-134. doi:org/10.20870/oeno-one.2010.44.3.1471

Riou Ch. and Lebon E., 2000. Application d'un modèle de bilan hydrique et de la mesure de la température de couvert au diagnostic du stress hydrique de la vigne à la parcelle. *Bulletin de l'OIV*, 73(837838), 755-764.

Roby G., Harbertson J.F., Adams D.A. and Matthews M.A., 2004. Berry size and vine water deficits as factors in winegrape composition: anthocyanins and tannins. *Australian Journal of Grape and Wine Research*, 10(2), 100-107. doi:10.1111/j.1755-0238.2004.tb00012.x

Rodríguez-Pérez J.R., Plant R.E., Lambert J.J. and Smart D.R., 2011. Using apparent soil electrical conductivity (ECa) to characterize vineyard soils of high clay content. *Precision Agriculture*, 12(6), 775-794. doi:10.1007/s11119-011-9220-y

Rossi R., Pollice A., Diago M.P., Oliveira M., Millan B., Bitella G., Amato M. and Tardaguila J., 2013. Using an automatic resistivity profiler soil sensor on-the-go in precision viticulture. *Sensors*, 13(1), 1121-1136. doi:10.3390/s130101121

Seguin G., 1983. Influence des terroirs viticoles sur la constitution et la qualité des vendanges. *Bulletin de l'OIV*, 56 (623), 3-18.

Seguin G., 1986. Terroirs and pedology of wine growing. *Experientia*, 42 (8), 861-873.

Soil Survey Staff, 1999. *Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys*. 2nd edition. Natural Resources Conservation Service, U.S. Department of Agriculture Handbook 436.

Sudduth K.A., Kitchen N.R., Wiebold W.J., Batchelor W.D., Bollero G.A., Bullock D.G., Clay D.E., Palm H.L., Pierce F.J., Schuler R.T. and Thelen K.D., 2005. Relating apparent electrical conductivity to soil properties across the north-central USA. *Computers and Electronics in Agriculture*, 46 (1-3), 263-283. https://doi.org/10.1016/j.compag.2004.11.010

Tardáguila J., Baluja J., Arpon L., Balda P. and Oliveira M., 2011. Variations of soil properties affect the vegetative growth and yield components of "Tempranillo" grapevines. *Precision Agriculture*, 12(5), 762-773. doi:10.1007/s11119-011-9219-4

Tisseyre B., Ojeda H. and Taylor J., 2007. New technologies and methodologies for site-specific viticulture. *Journal International des Sciences de la Vigne et du Vin*, 41 (2), 63-76. doi:org/10.20870/oeno-one.2007.41.2.852

Trought M., Dixon R., Mills T., Greven M., Agnew R., Mauk J.L. and Praat J.P., 2006. The impact of differences in soil texture within a vineyard on vine development and wine quality, pp 133-138. In *Proceedings of the VIth International Terroir Congress*, France.

Trought M.C.T., Dixon R., Mills T., Greven M., Agnew R., Mauk J.L. and Praat J.P., 2008. The impact of differences in soil texture within a vineyard on vine vigour, vine earliness and juice composition. *Journal International des Sciences de la Vigne et du Vin*, 42(2), 62-72. doi:org/10.20870/oeno-one.2008.42.2.828

van Leeuwen C., 2010. Terroir: the effect of the physical environment on vine growth, grape ripening and wine sensory attributes, pp 273-315. In Reynolds A.G. (ed) *Managing wine quality. Volume 1: viticulture and wine quality*, Woodhead Publishing.

van Leeuwen C. and Seguin G., 1994. Incidences de l'alimentation en eau de la vigne, appréciée par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (*Vitis vinifera* variété Cabernet franc, Saint-Émilion, 1990). *Journal International des Sciences de la Vigne et du Vin*, 28(2), 81-110. doi:org/10.20870/oeno-one.1994.28.2.1152

van Leeuwen C., Renouf V., Tregoat O., Marguerit E. and Roby J.P., 2008. Soils and plant material in prestigious Bordeaux vineyards. Impacts on yield and quality, pp 45-51. *In Proceedings of the VIIth International Terroir Congress*, Changins, Switzerland.

Walkley A. and Black I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37 (1), 29-38.

Wang S., Okamoto G., Hirano K., Lu J. and Zhang C., 2001. Effects of restricted rooting volume on vine growth and berry development of Kyoho grapevines. *American Journal of Enology and Viticulture*, 52 (3), 248-253.

Zerihun A., McClymont L., Lanyon D., Goodwin I. and Gibberd M., 2015. Deconvoluting effects of vine and soil properties on grape berry composition. *Journal of the Science of Food and Agriculture*, 95 (1), 193-203. doi:10.1002/jsfa.6705.