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Relationship between physical properties and the magnetic susceptibility in two soils of Valle del Cauca

Relación entre propiedades físicas y la susceptibilidad magnética en dos suelos del Valle del Cauca

Cristian Jiménez A.[1]; Jhony Benavides B.[2]; Daniel I. Ospina-Salazar[3]; Orlando Zúñiga E.[4]; Oscar Ochoa B.[5]; Carlos Mosquera G.[6]

1 M.Sc., Grupo de Investigación en Ciencias Ambientales y de la Tierra ILAMA, Universidad del Valle, Santiago de Cali, Colombia, cristian.o.jimenez@correounivalle.edu.co.
2 I.A., Grupo de Investigación en Ciencias Ambientales y de la Tierra ILAMA, Universidad del Valle, Santiago de Cali, Colombia, jhony.benavides@correounivalle.edu.co.
3 Ph.D., Grupo de Investigación en Ciencias Ambientales y de la Tierra ILAMA, Universidad del Valle, Santiago de Cali, Colombia, diospinas@unal.edu.co.
4 Profesor asociado, Ph.D., Universidad del Valle. Santiago de Cali, Colombia, orlando.zuniga@correounivalle.edu.co.
5 MBA., Agricultura de Precisión AgroAP S.A.S., Santiago de Cali, Colombia, oscar.ochoa@agroap.com.
6 MBA., Agricultura de Precisión AgroAP S.A.S., Santiago de Cali, Colombia, carlosmosquera@agroap.com.

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ABSTRACT

Magnetic susceptibility (MS) is a property that determines the degree of magnetization of a material according to its composition; therefore, it has potential in the assessment of agricultural soils. This study aimed to the application of this attribute to the physical analysis of soils, by determining its correlation with some physical properties in soils of Valle del Cauca. Samples were taken in two lots of sugar cane (Chondular and Santa Rosa), of 55 and 98 hectares, respectively. The lots were analyzed by descriptive statistics and spatial and Pearson correlation between MS and the physical properties of the soil, through a geographic information system software. High spatial correlations were found between MS and the properties analyzed, particularly sand and clay content (0.9

and -0.88, respectively, P<0.001) in Chondular lot, although correlations above 50% were also found with field capacity, thermal conductivity, bulk density and total pore space. Moreover, the correlations of MS were lower in Santa Rosa lot, being the most relevant in the order of 0.59 and -0.65 (P<0.005) also for sand and clay content respectively. These correlation differences were attributed to alterations due to soil tillage in Santa Rosa lot. The determination of MS and its spatial correlation with some physical properties of agricultural soils is a technique that could simplify its characterization, particularly the proportion of sand and clay.

Keywords: geospatial data, paramagnetism, pedotransfer functions, soil texture.

RESUMEN

La susceptibilidad magnética (SM) es una propiedad que determina el grado de magnetización de un material de acuerdo con su composición, dado su potencial en el diagnóstico de suelos agrícolas. Con el objetivo de evaluar la aplicabilidad de este atributo en el análisis físico de suelos, se determinó su correlación con algunas propiedades físicas en suelos del Valle del Cauca. Se realizaron muestreos en dos lotes de caña de azúcar (Chondular y Santa Rosa), de 55 y 98 hectáreas, respectivamente. Los datos se analizaron por estadísticos descriptivos, así como por matriz de correlación espacial y Pearson entre SM y las propiedades físicas del suelo, a través de un software de sistemas de información geográfica. Se encontraron correlaciones espaciales altas entre SM y las propiedades analizadas, particularmente con arenas y arcillas (0,9 y -0,88, respectivamente, P<0,001) en el lote Chondular, aunque también se encontraron correlaciones superiores al 50% con capacidad de campo, conductividad térmica, densidad aparente y espacio poroso total. Por otra parte, las correlaciones de SM fueron más bajas en el lote Santa Rosa, siendo las más relevantes del orden de 0,59 y -0,65 (P<0,005) para arenas y arcillas en su orden. Estas diferencias de correlación se atribuyeron a alteraciones por labranza del suelo en el lote Santa Rosa. De acuerdo con lo anterior, la determinación de SM y su correlación espacial con algunas propiedades físicas de suelos agrícolas, es una técnica que podría simplificar su caracterización, particularmente la proporción de arenas y arcillas.

Palabras clave: datos geoespaciales, funciones de edafotransferencia, paramagnetismo, textura del suelo.

INTRODUCTION

The survey of soils plays a key role in crop production, and mapping the spatial variability of soil properties is important for planning sustainable agricultural practices (Barbieri *et al.,* 2008). However, due to the high costs and time required for soil sampling, testing and analysis, its enforcement is not always spread among farmers. In order to make more efficient this practice, one alternative is to study physical attributes of matter (e.g. conductivity, refraction index, radiation emission, etc.) that can be correlated with soil properties such as texture, bulk density or hydraulic conductivity. These alternative tools for indirect estimation in soil survey have been called pedotransfer functions. According to McBratney *et al.* (2002) pedotransfer functions can be defined as mathematical models used to estimate the soil properties from other parameters measured with greater ease and lower cost. Some authors have suggested that there is great potential for using pedotransfer functions in countries where there is limited information or paucity of data from soils, in combination with remote sensing tools (Patil and Singh, 2016). Therefore, *in situ* and *ex situ* measurement of intensive physical properties, such as paramagnetism, is an option from which other soil attributes can be estimated.

Paramagnetism is a property of non-ferromagnetic elements (as aluminum and titanium) which is manifested in a transitory rearrangement of the electron spins in the presence of a magnetic field, which makes them attracted by it. In terms of magnetic susceptibility (MS), that is, the degree of magnetization of a given material under the influence of a magnetic field, ferromagnetic materials (iron, nickel, cobalt) exhibits very high values for this feature, in comparison with the paramagnetic ones, such as the above mentioned elements (Zúñiga *et al*., 2016). Magnetic susceptibility is the result of the translation and rotation of the electrons, which constitute the atoms of the minerals that are present in soils, sediments and rocks (Luque, 2008). Kanu *et al.* (2014) states that magnetic minerals present in soils may either be obtained from the parent rocks (lithogenic origin) during pedogenesis or because of anthropogenic activities, concluding that the content of magnetic minerals in the soil can broadly be expressed by its MS.

Numerous studies pointed out that the measurement of magnetic susceptibility can be very useful in the identification of properties related with factors and processes of soil formation, applied to soil mapping (Ramos *et al*., 2017). Magnetic susceptibility became popular in soil-related researches including paleoclimatic field studies (Huang *et al.,* 2006; Torrent *et al.,* 2010; Urcia *et al.,* 2012), soil erosion (Jordanova *et al.,* 2014; Rahimi *et al.,* 2013; Royall, 2001), and soil contamination by heavy metals (Pedroso, 2013). In addition, this technique has been tested to assist in the indirect quantification of soil properties that have magnetic expression in agricultural surveys (Mathé and Lévêque, 2003; Blundell *et al.,* 2009; Cortez *et al.,* 2011; Marques *et al.,* 2014). Whereas sampling and laboratory analysis are some of the more expensive steps and can hinder variability and application studies, magnetic susceptibility data can be used as a pedotransfer function to estimate clay and sand content with good accuracy (Siqueira *et al*., 2010). Studies such as those of Torrent *et al.* (2007) and Souza *et al*. (2010) have confirmed predictive potential of MS in relation to other soil attributes (physical, chemical and mineralogical) at different soil types.

Regarding the soil texture, for example, it has been observed that MS is associated with the nature of clay minerals and parent material (Camargo *et al.,* 2014), and that the magnetic properties of a soil along its profile are associated with the clay content and organic carbon in the different horizons (Bautista *et al.,* 2013). Marques *et al*. (2014) showed that the variability in soil properties can be represented by the spatial distribution of the MS, because this property (along with diffuse reflectance) express mineralogy, mainly clay, which in turn exhibits spatial variability correlated with spatial variability of soil attributes. Grimley *et al.* (2004) concluded that differences in critical MS values among their study site at Illinois (USA) seem to be controlled principally by surface soil texture and ambient pH. Dos Reis Barrios *et al.* (2017) studied the MS as an indicator of soil quality in sugarcane fields in southeastern Brazil, concluding that this feature can be used to identify changes in physical, chemical and mineralogical traits of Latosols under sugarcane harvested with and without previous burning, indicating the changes in soil quality. Ramos *et al*. (2017) reported that the limits indicated by a spatial boundary analysis based on MS values were effective to outline representative compartments of pedogenetic environments on the study area. Thus, the use of MS enables soil characterization to replace costly and time-consuming chemical and mineralogical soil analysis (Camargo *et al*., 2014).

The MS measurement for soil survey, complemented with computational tools such as software of geographic information, allow an alternative mapping of the study area in order to undertake corrective actions, optimize the tillage or spot any issue (e.g., slow hydraulic conductance associated with clay content). Hence, the aim of this work was to assess the spatial relationship of MS with several physical properties in two soils of southern Valle del Cauca region that could lead to an easier determination of these properties by correlation with MS.

MATERIALS AND METHODS

Location characteristics. The experiment was conducted in the south of Valle del Cauca department, Colombia, in the municipalities of Palmira and Candelaria. Measurements were done in two soils under cultivation of sugar cane, located specifically in two lots: Santa Rosa and Chondular. The Santa Rosa lot is located in Palmira, with geographical coordinates 3°35’05’’N-76°15’16’’W, altitude 1060 m.a.s.l., and average temperature of 22.8°C. The Chondular lot is located in Candelaria, with geographical coordinates 3°26’35’’N-76°22’45’’W, at an altitude of 967 m.a.s.l., and average temperature of 23.2°C (Figure 1). Total annual rainfall and relative humidity averages 1053.7mm and 81.9% in Santa Rosa, and 1023.1mm and 79.5% in Chondular, respectively, being both sites in the tropical dry forest ecological zone.

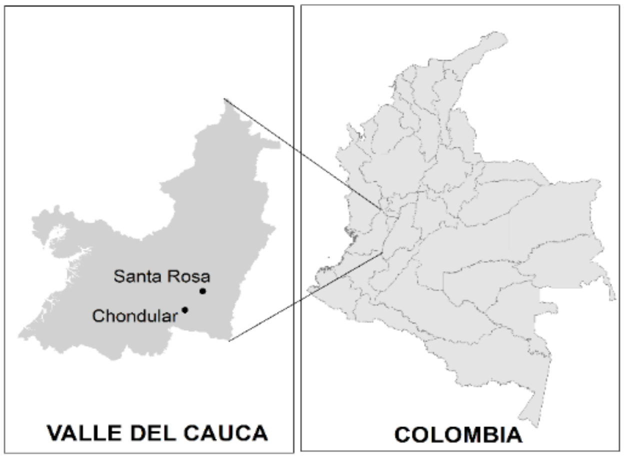


Figure 1. Location areas: Santa Rosa lot located in Palmira Municipality and Chondular lot located in Candelaria Municipality, in Valle del Cauca.

According to the study of soils conducted by IGAC - CVC (2004), in Santa Rosa lot dominates the Consociation of Pachic Haplustolls family, isohyperthermic, with fine texture, loamy PL symbol belonging to the Palmira complex soils. While in the Chondular lot, predominates the Consociation of Cumulic Haplustolls family, isohyperthermic, with fine texture, loamy MN symbol belonging to the Manuelita complex soils.

Soil sampling. Altered and unaltered soil samples were collected from 0 to 0.30m for physical analysis. Each sample was geo-referenced with a Garmin GPS, comprising an area of approximately 98.3 hectares in the lot Santa Rosa (subdivided in three irregular lots), and 55.3 hectares in the lot Chondular (subdivided in four irregular plots). Forty-two and 28 reference-sampling points were distributed for Santa Rosa and Chondular lots, respectively, with a density of one point per two hectares, as it is shown in (Figure 2).

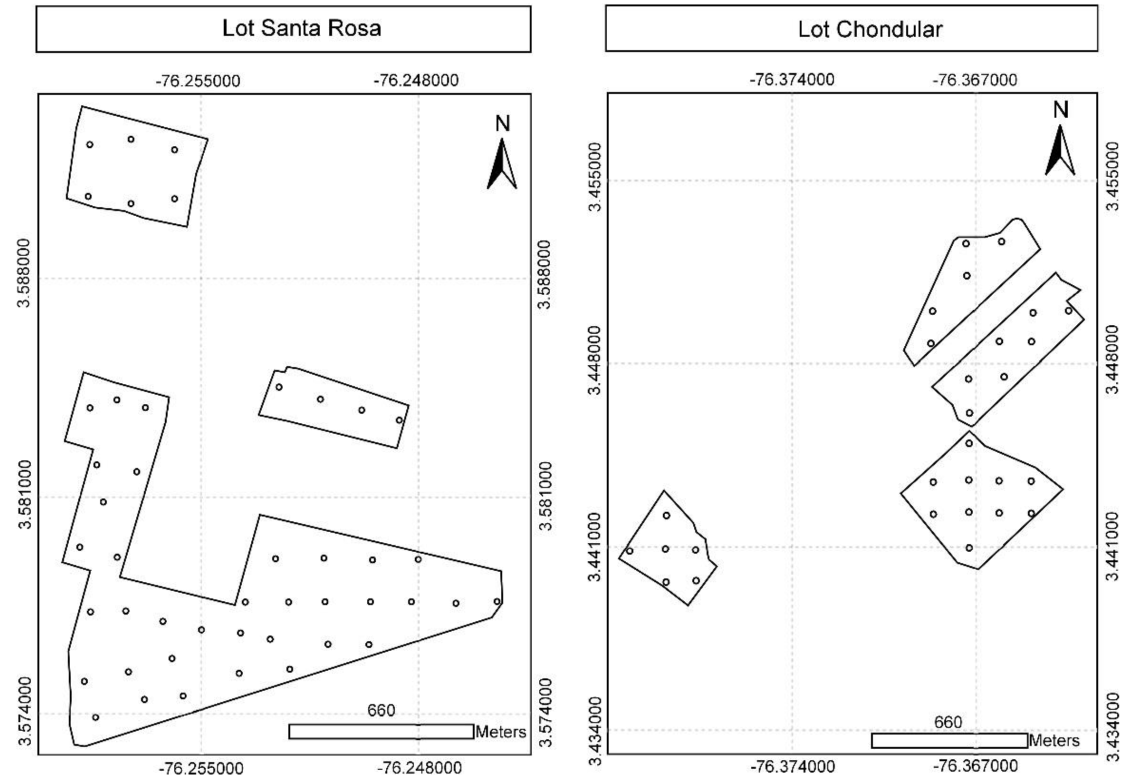


Figure 2. Distribution of sampling points in Santa Rosa (left) and Chondular lots (right).

Disturbed samples were taken with a bore, extracting four sub-samples within a radius of ten meters around the georeferenced point for the representative sample mixture. For the undisturbed samples three replicates per sampling point were taken, using a core auger-hole. The samples were processed for physical properties and determination of MS in the laboratory of Environmental Physics at Universidad del Valle in Cali - Colombia. Physical analysis included the determination of sand (S), clay (C) and silt (M), bulk density (BD), field capacity moisture (FC), drainable porosity (DP), total pore space (TPS), and thermal conductivity (TC) (Table 1).

Magnetic susceptibility determination. For the determination of MS, it was used a paramagnetic soil meter (PCSM Pike Agri-lab Supplies Inc., USA). According to the method developed by the authors of this paper, the altered soil samples were dried in an oven (40GC, Quincy Lab Corporation, USA) at 50°C for 12 hours, then passed through a sieve of 2mm size to separate the soil from rocks, roots and detritus. A sample of 25g was weighed and poured in a plastic cylindrical container of 4cm height and 2.5cm of diameter. Each container was placed in the paramagnetic soil meter device for one minute until obtain a steady value that shows the relative alignment of the electrons of the soil sample with the magnetic field generated.

Table 1. Physical properties of the soils analyzed.

No.	Properties	Symbol	Units	Method
1	Sand	S	%	Hydrometer - Bouyoucos
2	Clay	C	%	Hydrometer
3	Silt	M	%	Hydrometer
3	Field capacity	FC	%	Gravimetric (NTC 5167)
4	Thermal conductivity	TC	cal/cm·s·°C	Zúñiga and Reyes*
5	Bulk density	BD	$g.cm^{-3}$	Gravimetric (NTC 5167)
6	Total pore space	TPS	%	Gravimetric (NTC 5167)
8	Drainable porosity	DP	%	Gravimetric (NTC 5167)
9	Magnetic susceptibility	MS	dimensionless	Paramagnetism PCSM

[*] European patent No. 20030228. Zúñiga, O. and Reyes A. Universidad del Valle (2007).

Geospatial mapping and experimental design. The experimental design consisted in a randomized soil sampling across the two lots (Santa Rosa and Chondular), where the sampling points were evenly spread in the field (one point per two hectares) and georeferenced. The information obtained from the soil survey was processed with the software ArcMap of ArcGis 10.1 (ESRI, USA) in order to generate maps of each of the soil characteristics, including MS. The data set of the soil properties was analyzed by descriptive statistics, including a test of normality and Levene's test of homogeneity of variances. The geostatistical analysis was carried out using the ArcGis tool "Band collection statistics", a multivariate analysis from the covariance of each pair or layers, from which a correlation matrix is calculated. The correlation matrix shows the values of the correlation coefficients that represent the relationship between the two datasets, and is a measure of dependence between the layers. It is calculated from the covariance between the two layers divided by the product of their standard deviations. It is a number without units. In addition, a Pearson correlation of the data with corresponding significance t-test was done to complement the spatial correlation, using Minitab 17 program.

RESULTS AND DISCUSSION

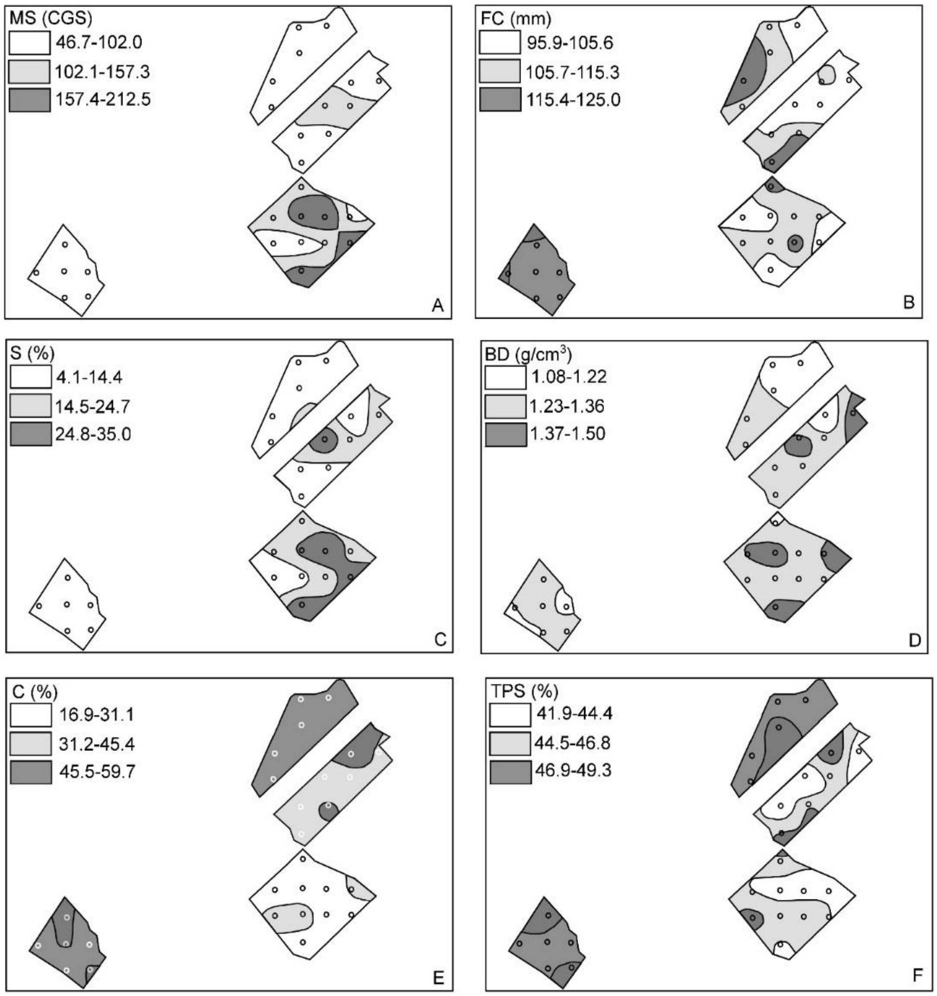
The descriptive analysis (Table 2) showed high variability of MS in both experimental locations, with values of 44.9% and 42.8%, for Santa Rosa and Chondular lots, respectively. Properties such as total pore space, field capacity and bulk density showed less variability within the study areas.

Despite the high variability of the data of MS, when comparing these values with sand and clay content in Chondular lot, a consistent trend was observed, *i.e.*, the areas of high MS match with the areas of high content of sand and the areas of low content of clay (Figure 3). Further relationships were also detected between MS and other properties such as field capacity, bulk density and total pore space, although its correspondence with the former variable was not particularly evident.

Table 2. Descriptive statistics for the physical properties of soil.

	Lot Chondular					Lot Santa Rosa				
	Min	**Max**	**Mean**	**SD**	**CV**	**Min**	**Max**	**Mean**	**SD**	**CV**
S	4.1	35	15.1	7.4	49	14.4	59.3	32.9	9.9	30.1
C	16.9	59.8	40.3	12	29.8	16.1	45.4	31.2	5.8	18.7
M	31.1	62.8	44.6	8.1	18.1	21.5	48	35.9	5.6	15.6
FC	32.0	41.7	36.5	2.3	6.4	25.6	40.8	34.1	2.9	8.5
TC	0.73	1.26	0.96	0.10	10.42	0.56	1.25	0.83	0.15	18.07
BD	1.1	1.5	1.3	0.1	5.4	1.1	1.7	1.4	0.1	6.6
TPS	41.9	49.3	45.8	1.7	3.8	37.7	52.4	44.7	2.7	6
DP	6.1	15.8	9.3	2.1	22.7	2.9	18	10.6	3.3	30.7
MS	46.7	212.5	98.1	42	42.8	36.6	195.9	89.6	40.3	44.9

CV: Coefficient of variation. SD: Standard deviation.



A: Spatial distribution of Magnetic Susceptibility (MS). B: field capacity (FC). C: sand (S). D: bulk density (BD). E: clay (C). F: total pore space (TPS).

Figure 3. Spatial distribution of soil properties in Chondular lot.

Figure 4 shows the values of MS, clay and sand for Santa Rosa lot. In these maps it can be observed the spatial distribution of MS (A), sand (B) and clay content (C), in which the same apparent relation with sand and clay was detected, although unlike Chondular lot, the matching of MS with the areas of high content of sand and low content of clay was only partial.

The relationship between the figures displayed in Figures 3 and 4 analyzed by correlation matrix in ArcGis and Pearson correlation are shown in Table 3. It is corroborated the high and significant correlation between sand and clay content with MS in both locations, being more consistent that of Chondular lot. However, MS did not exhibit a coherent trend with silt and total pore space, in view that it showed a positive and negative correlation in Chondular and Santa Rosa lots, respectively. Field capacity, thermal conductivity and bulk density had higher and significant (P<0.01) spatial correlations with MS in Chondular, whereas these correlations were less appreciable in Santa Rosa location. For drainable porosity, there was little correlation and significance with MS in both sites.

Further analysis of the correlation between MS and sand/clay is depicted as dispersion diagrams in Figure 5, of each sampling point with its corresponding value of MS contrasted with that of sand and clay. The determination coefficient revealed the same pattern of direct and inverse relation of the latter properties with MS at both sites, although this relation was not as accurate in Santa Rosa as it was in Chondular lot.

The expression levels of MS can be related to the texture composition (Williams and Cooper, 1990). Matias *et al*. (2014) found correlations between different physicochemical properties of oxisols and MS, but unlike this work, their results showed that the relation with sand and clay are negative and positive, respectively, and concluded that the spatial variability of MS can be used to infer on clay content and soil base saturation variability. Aversely,

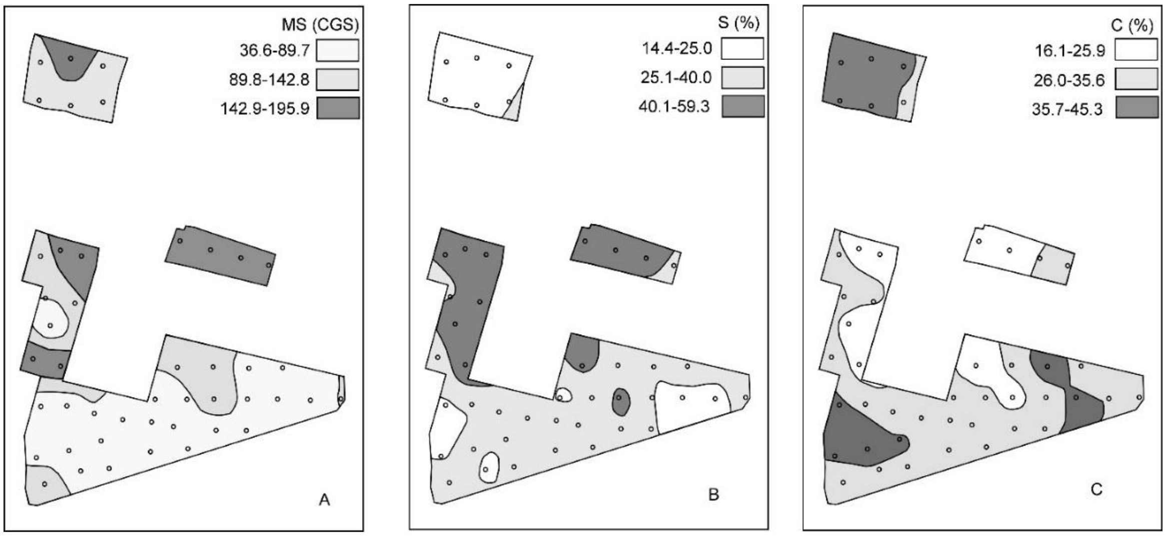


Figure 4. Spatial distribution of soil properties in Santa Rosa lot. A: MS. B: sand. C: clay.

but supporting the results of the present investigation, Siqueira *et al*. (2010) found a positive relation of MS with clay content. In relation with this, it is important to consider that the nature of the clay minerals and MS is dependent on the variation of the soil parent material (Camargo *et al*., 2014).

The presence of ferromagnetic iron in the molecular structure of clays seems to be determinant for the expression of MS. The results reported by Ramos *et al*. (2017), emphasized that magnetism is most evident in clayey soils. Among the ferromagnetic minerals, magnetite is more easily found in coarser soil fractions, such as sand and silt, whereas maghemite is mostly found in finer fractions, such as clay. Grimley *et al.* (2004) found MS values consistently higher in well-drained soils and lower in hydric soils, reflecting anaerobic deterioration of both detrital magnetite and soil-formed ferrimagnetics. The latter authors indicated that the higher magnetite content and slower dissolution rate in sandy soils might explain the difference. This in part corroborates the findings of this study, in which the highest MS values were observed in the areas of sandy texture. Hence, it is possible that the water retention capacity of the soil related with its texture and the degradation of magnetite were the mechanism that elicits the paramagnetic response. Other researchers mention that the magnetic behavior is in fact more evident in soils whose clay fraction is greater because in clay, magnetite is oxidized to maghemite, while in the sand fraction, magnetite is oxidized directly to hematite that has lower MS than magnetite (Fontes *et al.*, 2000). Highly variable critical MS values in areas of South Africa, probably a result of differing magnetite contents in soil parent materials among the sites, show the need for calibration of critical MS values on a site specific basis (Grimley *et al.,* 2004). However, these authors also informed that MS values of clayey soils are significantly lower than those of sandy loam soils in the same landscape position, which is consistent with the values here reported. For these reasons, the identification of high spatial correlation between MS and the contents of clay and sand could be an alternative for inferring other texture-related parameters, such as hydraulic conductance.

Table 3. Coefficients of spatial and Pearson correlation between MS and the physical properties of the soil evaluated.

	Chondular			**Santa Rosa**		
	Correlation matrix	**Pearson**	**P value**	**Correlation matrix**	**Pearson**	**P value**
S	0.898	0.878	0.000	0.588	0.572	0.002
C	-0.877	-0.846	0.000	-0.648	-0.622	0.002
M	0.478	0.345	0.072	-0.367	-0.373	0.015
FC	-0.536	-0.622	0.000	-0.204	-0.221	0.159
TC	-0.766	-0.671	0.000	-0.162	-0.179	0.256
BD	0.610	0.512	0.005	0.098	0.065	0.685
TPS	-0.685	-0.630	0.000	0.060	0.082	0.605
DP	0.034	0.172	0.382	0.232	0.263	0.092

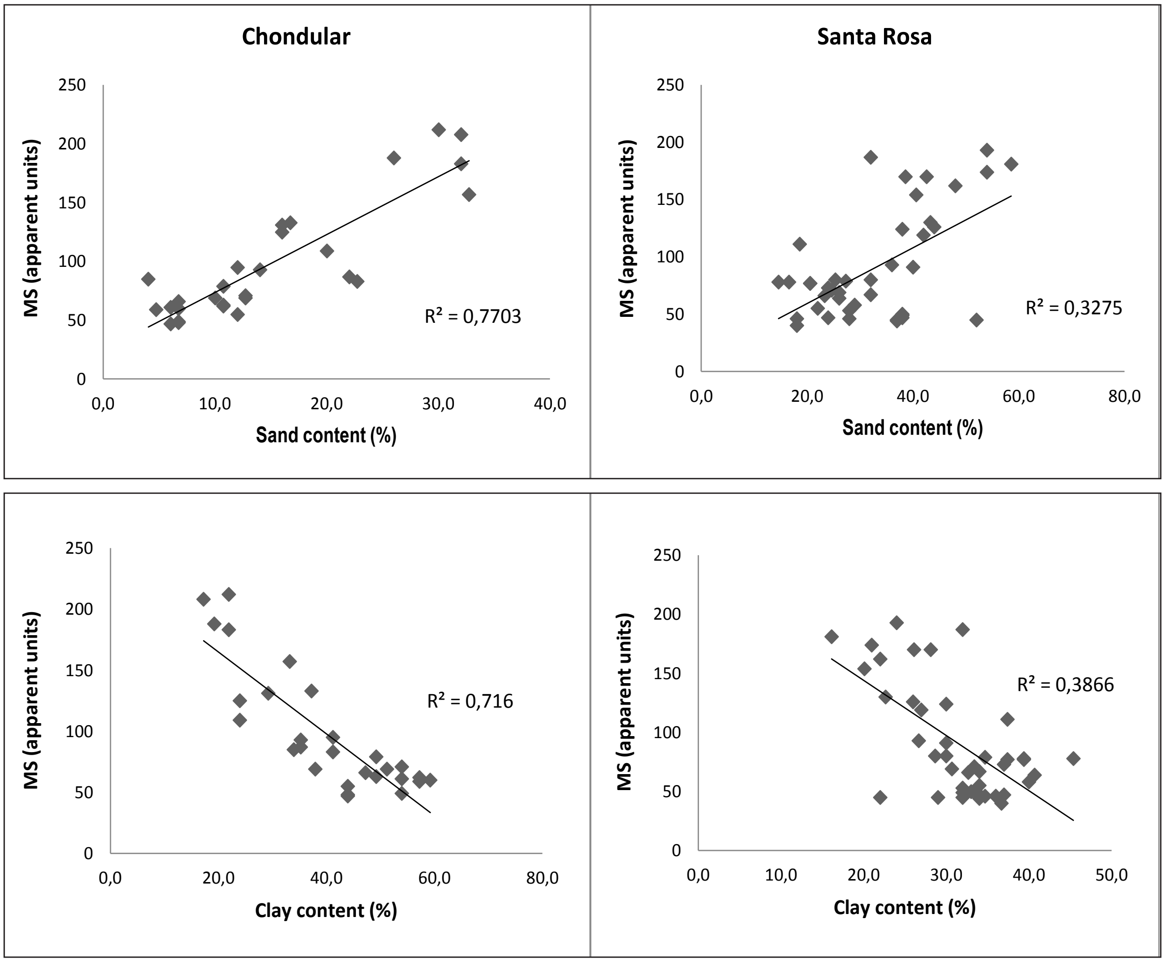


Figure 5. Dispersion diagram of sand and clay content versus MS in Chondular (left) and Santa Rosa (right).

The relationship between MS and the other physical properties (BD, TPS, FC and DP) can be inferred from the content of clay and sand. Regarding clay, a high content lead to a greater formation of micropores, responsible for water retention in the soil; since microporosity predominates in clayey soils, it occupies most of the total pore space, whereby there is a direct relationship between clay and microporosity. In addition, soil micropores allow greater heat conductance (Gutiérrez *et al.*, 2016), which explains its correlation with thermal conductivity. Moreover, a high content of sand lead to a higher bulk density in the soil, because it is a heavier and thicker material which in turn contributes to the formation of macropores, improving drainable porosity.

It is also important to determine the extent of tillage influence on MS in the selected sampling points. The correlation values (and the coefficient of variation of the properties that rely on the structure, like bulk density and pore space) observed in Santa Rosa were lower and less significant than in Chondular, which is attributed to a recent tillage in the area prior to the sampling. This is an issue previously mentioned by Mathé *et al.* (2003), who reported magnetic anomalies in marshland soils recently tilled.

Uniform mineralogy is typical for both surface soils and samples from different depths in non-disturbed soil profile (Jordanova *et al.*, 2011). This supports the hypothesis that, within the studied area, the observed magnetic differences comes from variations in soil movement and redistribution of the ferromagnetic carriers due to tillage operations. This statement agrees with previous results (Nazarok *et al*., 2014), who indicated that soil MS has a high degree of statistical relationship with erosion index and humus content, both parameters highly dependent on human intervention.

As pointed out by Grimley *et al.* (2004), more research is required to validate the MS method according to the different regions, land uses, soil types and parent materials. It is important to determine and compare its critical values in contrasting sites to develop an accurate database.

CONCLUSIONS

The significant correlation values (either by spatial matrix or Pearson) between MS and soil particle composition (particularly clay and sand percentage), are evidence of this property as a pedotransfer function for texture determination. The lack of correlation with silt content could be avoided by the proper determination of sand and clay through MS. However, this parameter might not be suitable as a pedotransfer function for other physical properties such as total pore space, drainable porosity and bulk density. Moreover, the physical disturbance of the soil by tillage, that alters the attributes dependent on the soil structure (like bulk density and pore space), also affects the expression of MS and therefore its correlation with these variables. Notwithstanding the above stated, MS could be a proper tool to the indirect quantification of soil texture with measurable paramagnetism. It must be considered the degree of physical disturbance of the soil that impairs the accuracy of MS as a function of other physical properties.

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