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Soil magnetic susceptibility and its relationship with naturally occurring processes and soil attributes in pedosphere, in a tropical environment

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ABSTRACT

Soil magnetic susceptibility (κ) has potential to be used as a pedoenvironmental indicator from which mineralogy, pedogeochemical, pedogeomorphological and pedogenic processes can be inferred. It can be used in pedosphere studies, as an auxiliary information for appropriate and sustainable soil use and management. This research aimed to analyze how pedogenesis and geochemical processes affect the κ and some of its attributes, as well as its potential use in discriminating soil great groups, following the digital soil mapping approach. The study area is located in São Paulo State - Brazil. Soil samples were collected for physical–chemical analysis from 79 locations (0–20 cm depth). At these sites, magnetic susceptibility was measured with a portable field instrument and analyzed in terms of geology, relief and soil class. The results showed that geology strongly affects κ, mainly in diabase derived soils, followed by metamorphosed siltstone and siltstone. In fluvial sediments, the κ exhibits different behaviors due to different sediments deposited by the Capivari River. In less evolved soils, such as Cambisols, lithology is a more important contributor to κ than pedogenesis. In more evolved soils, pedogenesis increases κ, whereas argilluviation/ferralitization reduces it. The κ values did not decrease significantly or even increase downslope, due to the presence of diabase on the lower parts. Differences in κ where observed between diabase bedrock located in different parts of the study area, indicating more of an influence by geomorphic processes rather than lithology. With respect to soil attributes, positive correlations between κ and base saturation, cation exchange capacity, organic matter, and iron and clay content were found, whereas a negative correlation was found between κ and sand content. The κ correlates with changes in lithology and soil class demonstrating its application as a potential tool for the discrimination of soil great groups and digital soil mapping.

1. Introduction

World population is expected to reach nine billion people by 2050, and the production of food and fiber to meet their demand is expected to double (Godfray et al. 2010). Knowing that worldwide agroforestry activities depend on soil as a primary resource for production of crops (FAOSTAT, 2003), recognition of soil as an essential environmental component for the maintenance of human life and the production of fiber and food is vital (Robinson et al. 2017).

There is a tendency to expand agricultural frontiers into new areas, with consequent environmental impact and degradation of agroecosystems (Godfray et al., 2010). The main environmental processes that occur in the pedosphere are weathering, pedogeomorphological, pedogeochemical and pedogenesis.

Pedogeomorphological processes such as denudation, erosion and infilling of canyons are related to landscape evolution (Atalay et al., 2018). Pedogeochemical processes are geochemical pathways that result in mineral formation and soil profile differentiation (Paisani et al., 2013). Pedogenesis is related to geochemical and biological pathways resulting in differentiation of soil classes and horizons (Breemen and Buurman, 2003). Therefore, knowledge of soil attributes and the natural processes that occur in the pedosphere are essential to evaluate the soil's capacity for land use and management, as well as mitigation or prevention of environmental degradation (Li and Heap, 2008; Foley, 2011).

Among soil attributes, κ is one of the closest related to processes that

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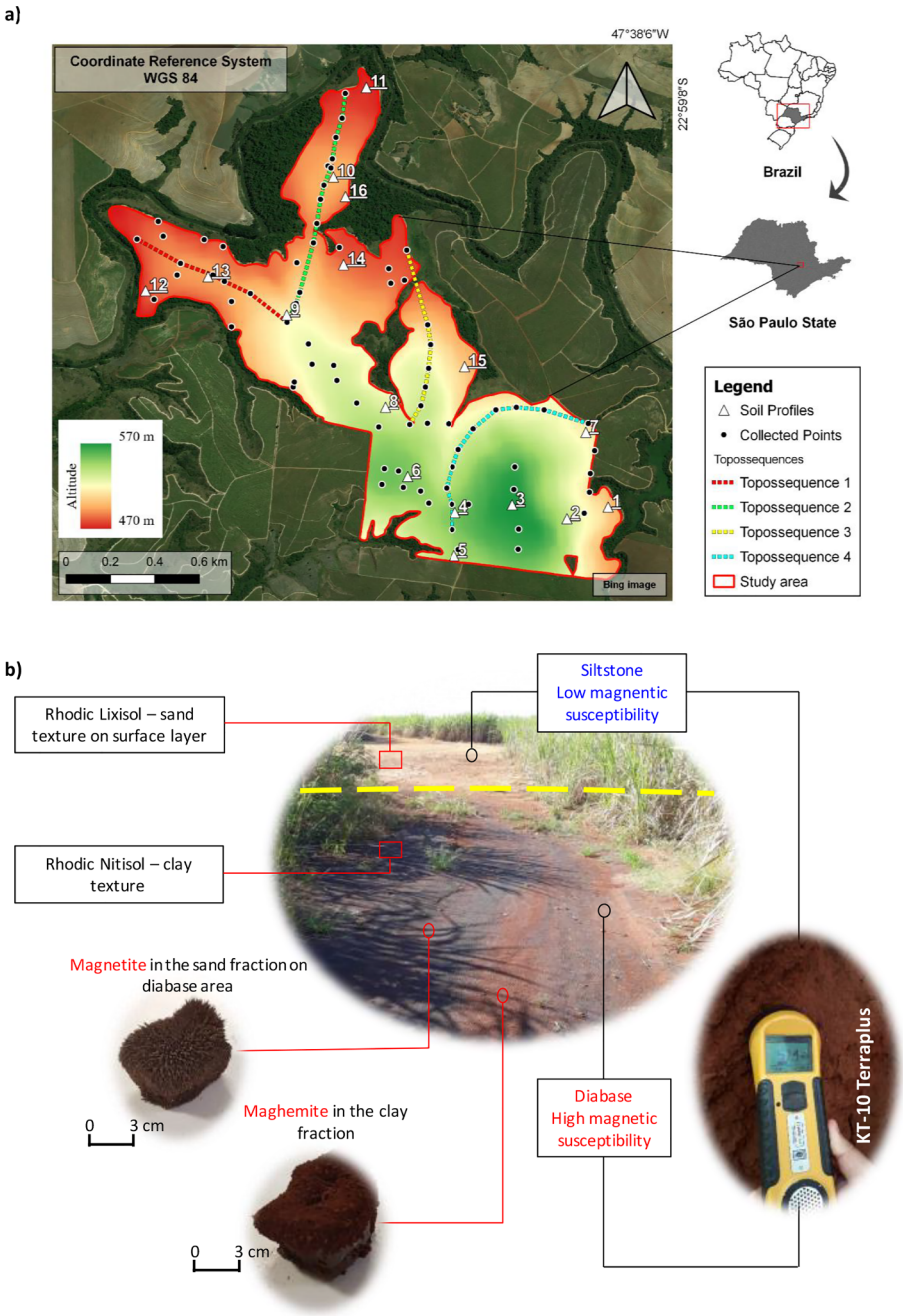

Fig. 1. a) Study area, collected points and selected topossequences. b) Susceptibilimeter (KT-10 Terraplus) reading soil surface and some of soil classes and minerals magnetically quantified.

occur in the pedosphere (Singer et al., 1996; Sarmast et al., 2017). Magnetic susceptibility is the degree to which a substance can be magnetized (Rochette et al., 1992) and is defined as $M = [\kappa] \times H$, where M is the induced magnetization of the material and H is the inductive magnetic field. Magnetic susceptibility is used to study geology (Shenggao, 2000), texture and organic carbon (Camargo et al., 2014; Jiménez et al., 2017), soil degradation (Mokhtari Karchegani et al., 2011), soil pollution (Yurtseven-Sandker & Cioppa, 2016; Rachwał et al., 2017), water balance (Valaee et al., 2016) and soil survey (Grimley et al., 2004). Thus, pedologists use soil magnetism to understand pedogenetic and pedogeomorphological processes (McFadden and Scott, 2013; Sarmast et al., 2017).

Magnetic susceptibility is important for the study of tropical soils, especially in areas on top of basaltic spills (Da Costa et al., 1999), because it allows quick, safe and nondestructive means of iron-containing minerals in rocks, soils and sediments (Dearing, 1994).

Iron containing minerals can be classified as: ferromagnetic, ferrimagnetic, paramagnetic or anti-ferromagnetic (Dearing, 1999). Magnetic properties of the soil as determined by geophysical techniques, such as κ, reflect the presence of ferrimagnetic minerals in the clay and sand fractions, such as maghemite and magnetite, respectively, as well as other minerals such as ferrihydrite and hematite. (Valaee et al., 2016). Magnetic susceptibility also allows inference of soil formation processes and source materials (Mullins, 1977; De Jong et al., 2000; Jordanova, 2016). Soil magnetometry is applied in geosciences and environmental sciences to detect presence of ferrimagnetic minerals (Ayoubi and Mirsaidi, 2019; Hu et al., 2020; Jordanova et al., 2019).

The composition of the source material and consequently the

mineralogy of the rocks and sediments that formed the soils, are the main parameters influencing magnetic properties (Ayoubi et al., 2018). However, there are many environmental variables acting in the κ pedosphere, such as the stage of landscape evolution, soil formation processes, source material, biological activity, soil hydrology, physical–chemical properties and human activities (Spassov et al., 2004).

Some studies used laboratory methods to identify soil magnetic signatures (Grimley et al., 2004; Van Dam et al., 2004; Siqueira et al., 2010; Marques et al., 2014; Jordanova et al., 2016; Jiménez et al., 2017; Kanu et al., 2019;) . However, the most studies focused on the results of κ without relating it to naturally occurring processes in the pedosphere (pedogeochemical, pedogenesis and pedogeomorphological) (Cervi et al., 2019). In addition, there is also a paucity of research demonstrating how κ can be used as a tool in soil classification and digital soil mapping (Sarmast et al., 2017; Cervi et al., 2019). In Brazil, there is little data of soil κ (Samuel-Rosa et al., 2020). By contributing to this knowledge gap, it is possible to improve κ applications in soil science (Grunwald et al., 2011; Brevik et al., 2016), similar to research undertaken by Santoso et al. (2019), who correlated soil pH and κ to soil fertility levels. More research is necessary to verify the potential use of soil magnetic signatures, in the field to distinguish variations in lithology and their relation to pedosphere processes, soil classes and water regimes (Cervi et al., 2019).

This research is based on two hypotheses: *i)* natural occurring processes in the pedosphere lying on different parent material and relief affect soil κ and its attributes and; *ii)* the field sensors detect variability in soil κ according to the characteristic of the pedoenvironment.

Given this, the research aimed to assess the relationship between surficial soil κ and natural processes in the pedosphere along with soil attributes across a heterogeneous tropical environment in Brazil. For that, we 1) characterized κ in the top soil (0–20 cm depth), 2) related κ to soil attributes (texture, base saturation, cation exchange capacity, total iron content and organic matter) and 3) used κ to discriminate soil class.

This research may provide the basis for improving techniques in soil surveys and digital soil mapping (Cervi et al., 2019), through greater understanding of pedogenetic, geochemical, pedogeomorphological and environmental processes that occur in soil (Rahimi et al. 2013; Ayoubi et al. 2019; Govedarica et al. 2019).

2. Material and methods

2.1. Study area, soil samples and laboratory analysis

The study site lies within Peripheral Depression of São Paulo in the Capivari River watershed. The area occupies 183 ha and is currently cultivated with sugar-cane. (Fig. 1). The lithology is composed of sedimentary (siltstones) and metamorphic rocks (metamorphosed siltstones), diabase intrusive dikes and river sediments (Fig. 2a). The relief is variable, with altitudes ranging from 474.83 m to 567.69 m and a maximum slope of 35%. According to the Köppen classification, the climate is subtropical mesothermal (Cwa), with an average annual precipitation of 1200 mm (Alvares et al., 2013), and average temperatures of 18 °C in winter and 22° C in summer.

Due to the lithological variability and heterogeneous relief, the diversity of soils in the area fall into several taxonomic classes, which in previous works by Bazaglia Filho (2012) were classified as Acrisols, Lixisols, Nitisols, Cambisols and Phaeozems (IUSS Working Group WRB, 2015) (Fig. 2d). We used a detailed soil class map as reference for investigating the relationship between the distribution of soil classes and κ patterns.

For the physical–chemical analysis, 79 soil samples were collected across the area at a depth of 0–20 cm using an auger (Fig. 1). Each point was georeferenced. The particle size analysis was performed using the densimeter method following methodology proposed by Camargo et al. (1986) in which the samples were air dried, ground and passed through a 2 mm sieve. Subsequently the definitions of the textural groups were determined according to EMBRAPA (2011). Both wet and dry colors of the samples were determined using the Munsell chart. Exchangeable cations, magnesium (Mg), calcium (Ca) and aluminum (Al^{3+}), were determined by atomic absorption spectrophotometer after extraction with 1 M KCl solution. The potassium cation (K^+), was quantified by Mehlich-1 using a flame photometer (EMBRAPA, 2017). Potential acidity ($H^+ + Al^{3+}$) was determined by the SMP method (Quaggio and Raij, 2001) and the pH in water by EMBRAPA methodology (2017). The organic matter (OM) content was determined following the Walkley-Black method (Walkley and Black, 1934). Iron contents were determined by sulfuric digestion (Lim and Jackson, 1986). Silicon (SiO_2) and titanium (TiO_2) contents were determined following the methodology of EMBRAPA (2017). Subsequently, the parameters, base sum (BS) base saturation (V%), aluminum saturation (m%) and cation exchange capacity (CEC) were calculated using the analytical data obtained.

2.2. Magnetic susceptibility (κ)

Surface readings of κ were recorded at all 79 points using a near geophysical susceptibility sensor (SC), model *KT10 - Terraplus* (Fig. 1b), which measures the soil κ to a depth of 2 cm below the surface, with a precision $10^{-6}SI$ units, in $m^3\ kg^{-1}$.

First, the sensor was calibrated by determining the frequency of the outdoor oscillator. Next the frequency directly above the ground was measured with the SC and finally the frequency was measured again in the open air. This procedure was necessary because the operating principle of the device is based on the difference between the κ of the material in the ground and the ambient outdoor value. Scanner mode readings were applied, which used the best geometric correlation to direct κ readings, providing fast and accurate quantification. The average of three readings were made in triangulation around the auger collection points to reduce noise.

2.3. Digital elevation model generation and maps

Using SAGA GIS (2.1.2) software (*Terrain Analysis Tool*), the digital elevation model (DEM) was created from the tabulated database, using altitude and georeferenced points. Four toposequences (T1 – T4) were defined and plotted (Fig. 1a) using the ArcGIS 10.3 software (Esri, 2011), where lithology, soil class and relief information were concatenated in order to analyze the distribution of κ with respect to the landscape.

2.4. Statistical analysis

The soil data set originally contained 79 soil samples. However, after carefully analyzing the data, some outliers related to sensor readings noise were excluded. Thus, the final dataset used for statistical analysis contained 71 valid samples.

Analysis of variance (ANOVA) and mean comparison by Tukey ($p < 0.05$) using R software (R Core Team, 2015) were performed to identify and evaluate significant differences between κ values, lithological components and soil (more and less evolved). The ANOVA was performed considering *type III error* to verify statistical differences between κ of lithological components and soil classes. In this step, the *R emmeans* (*estimated marginal means*) package was used to consider estimations for unbalanced data. The Tukey test was performed using *multcomp* (*Simultaneous Inference in General Parametric Models*) package. Additionally, descriptive statistics of κ maximum, minimum, mean, median, standard deviation (SD) and coefficient of variation (CV) were calculated considering κ, lithology and soil class. Pearson's correlation analysis was carried out between κ and soil attributes to look for relationships.

In ArcGIS 10.3 software (Esri, 2011), the spatial distribution of the κ

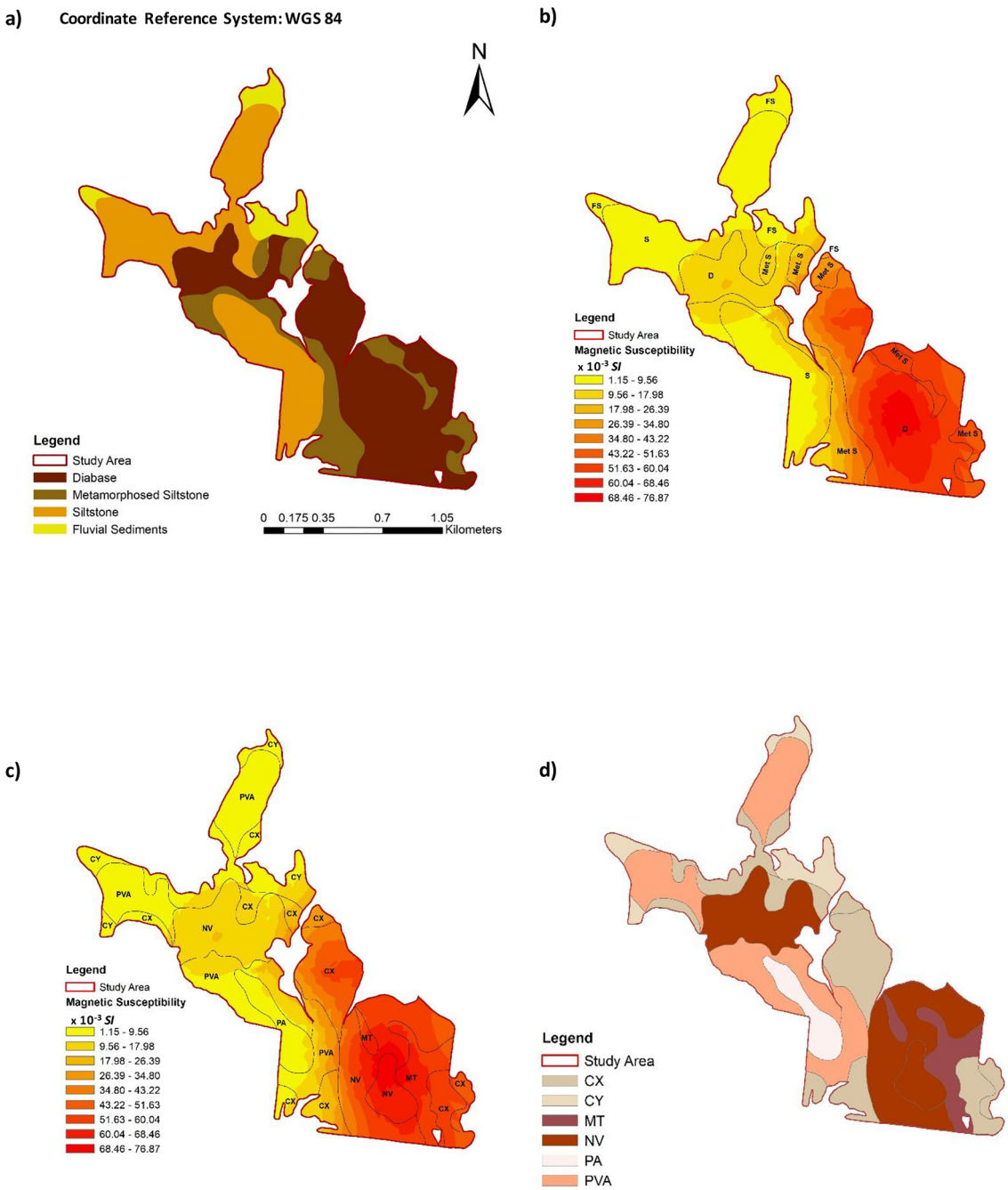

Fig. 2. a) Geological compartments. b) Magnetic Susceptibility and Geology: D: Diabase; Met S: Metamorphosed Siltstone; S: Siltstone; FS: Fluvial sediments. c) Magnetic Susceptibility and soil classes: CX: Haplic Cambisols, CY: Fluvic Cambisols, MT: Luvic Phaozem, NV: Rhodic Nitisol: PA: Xanthic Acrisol, PVA: Rhodic Lixisol. The geological and Soil classes maps were adapted from Bazaglia Filho et. al. (2012).

values (Fig. 3 and toposequences with predicted values) was obtained by geostatistical *Spatial Analyst Tools - Interpolation* - Kriging method. The experimental semivariogram was estimated as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2$$

γ (h): semivariance;
N (h): number of pair of points separated by the distance h; $z(x_i)$: value of z in the position x_i;
z $(x_i + h)$: value of z in the position $x_i + h$.

After calculating the semivariogram, the interpolation was undertaken by ordinary kriging, estimated as:

$$\hat{z}(x_0) = \sum_{i=1}^{N} \lambda_i z(x_i)$$

$\hat{z}$ (x_0) is the kriging estimator at the point x_0;
z (x_i) represents the measured value at the point x_i;
λ_i is the kriging weight attributed to the $z(x_i)$ values closest to the estimate $\hat{z}$ (x_0).

3. Results and discussion

3.1. Relationship of magnetic susceptibility with lithology and mineralogy

The summary statistics of κ values demonstrated significant

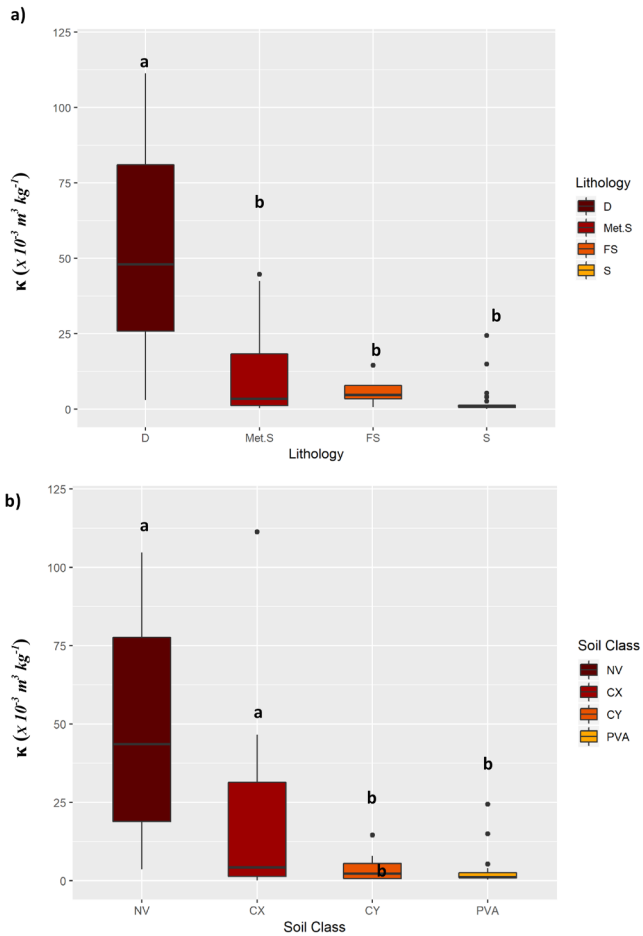

Fig. 3. *Boxplot* for magnetic susceptibility (K). Multi comparison test for lithology (a) and soil classes (b), significant at the 0.1 significance level., respectively. Geology abbreviation; D: diabase, FS: fluvial sediments, MS: metamorphosed siltstone, S: siltstone. Soil classes abbreviation: CX: Haplic Cambisols, CY: Fluvic Cambisols, NV: Rhodic Nitisol, PVA: Rhodic Lixisol.

Table 1
Descriptive statistics for the analyzed magnetic susceptibility by lithological compartments.

Summary Statistics	κ (× 10^{-3} m^3 kg^{-1})			
	D	Met. S	S	FS
Mean	53.81	12.02	2.40	6.24
Standard deviation	35.10	16.33	4.82	5.34
Minimum	2.99	0.42	0.07	0.63
Maximum	111.33	44.67	24.36	14.6
Count	22	12	32	5

κ: Magnetic susceptibility units (× 10^{-3} m^3 kg^{-1}). D: Diabase. Met. S: Metamorphosed Siltstone. S: Siltstone. FS: Fluvial Sediments.

differences as a function of lithology (Table 1 and Fig. 3a). The mean value of κ for diabase is four times the mean value of κ for metamorphosed siltstone (Table 1). These discrepancies were also reported by Sarmast et al. (2017) and Rachwał et al. (2017), who attributed these differences to variability in mineralogical and chemical compositions of rocks and minerals, as well as the geochemical behavior of minerals. The decrease in κ from diabase to other lithological components (Fig. 3a) can be explained by the higher occurrence of ferrimagnetic minerals in the diabase (mafic igneous rock) (Mullins, 1977). Intermediate values of κ are due to the strong influence of the iron minerals in diabase on the surrounding metamorphosed siltstone (Sawyer, 1986). The lowest values can be explained by the low ferrimagnetic mineral content in siltstone and river sediments (Fig. 1a).

Some *outliers* were observed with above average κ values for the siltstone (Fig. 3a). This can be explained by transport and concentration of magnetite derived from diabase at higher altitudes to lower altitudes, which was observed in the field. In addition, it could occur due to the variability in the source material of the sediments transported along the sedimentary cycle. There may have been higher concentrations of ferrimagnetic minerals at specific places in this rock, still formation of magnetite and hematite by hydrothermal alterations (Hooper, 1987).

The highest mean value of κ (53.81 × 10^{-3} m^3 kg^{-1}) (Table 1) was observed in soils derived from diabase. Singer and Fine (1989), Shenggao (2000), Damaceno et al. (2017) and Su et al. (2015) analyzed κ in soils derived from different source materials and found higher values in soils derived from this same rock. This is because mafic rocks are rich in ferrimagnetic minerals (Aydin et al., 2007) which release iron into the system through weathering (De Jong et al., 2000; Cervi et al., 2019), especially in free and hot drainage environments, favoring the formation of ferrimagnetic minerals such as magnetite and maghemite (Schwertmann, 1988; Grimley and Vepraskas, 2000; Maxbauer et al., 2016).

According to Dearing et al. (1996) and Maher et al. (2003), the climate associated with iron release rates from parent materials, under the weathering action and regional pedoclimate controls are determining factors in κ variability in soil. This is due to the formation of pedogenic ferrimagnetic minerals, such as magnetite and maghemite in soils developed on the same lithology (Shenggao, 2000). However, the interpolated κ map (Fig. 2b) reveals discrepancies between the east and west diabase areas, which also revealed in the summary statistics (Table 2). The explanation for this difference is probably related to the persistence of ferrimagnetic minerals (Lourenço et al., 2014; Grison et al., 2016); different mineralogical compositions of diabase and/or ferralitization operating at different rates (Smith and Rose, 1975).

Intermediate mean values of κ (12.02 × 10^{-3} m^3 kg^{-1}) (Table 1) were found in the metamorphosed siltstone. Due to the influence of a diabase intrusion into the siltstone which may have enriched iron-bearing minerals due to the mobility of this element during metamorphism (Sawyer, 1986), repositioning on metamorphic rocks (Hooper, 1987) and/or magnetite formation from metamorphosed rocks (GRANT U.S., 1900). According to Hooper (1987), this iron enrichment occurs as a mixed mass of magnetite and hematite in fractures. In addition, according to Schwertmann (1988), Roman et al. (2013) and Jordanova et al. (2019), maghemite and magnetite can form as a result of past fires which produce higher temperatures, reduce OM and oxygen in soil pores, thus, allowing the formation of magnetite through reduction of hematite and subsequent reoxidation to maghemite: both minerals have high κ (Le Borgne, 1955; Le Borgne, 1960; Tunstall et al., 1976).

The lower κ values (2.40 × 10^{-3} m^3 kg^{-1}) (Table 1) in soils over siltstones is likely due to low content of ferri and antiferrimagnetic minerals in the parent material and predominance of para and diamagnetic minerals. The low κ values reaffirm the silica rich mineralogy

Table 2
Descriptive statistics for the analyzed magnetic susceptibility by two diabase areas (east and west).

Summary Statistics	κ (× 10^{-3} m^3 kg^{-1})	
	Diabase east	Diabase west
Mean	66.51	19.94
Standard deviation	31.45	17.76
Minimum	13.07	2.99
Maximum	111.33	49.4
Count	16	6

κ: Magnetic susceptibility units (X 10^{-3} m^3 kg^{-1}).

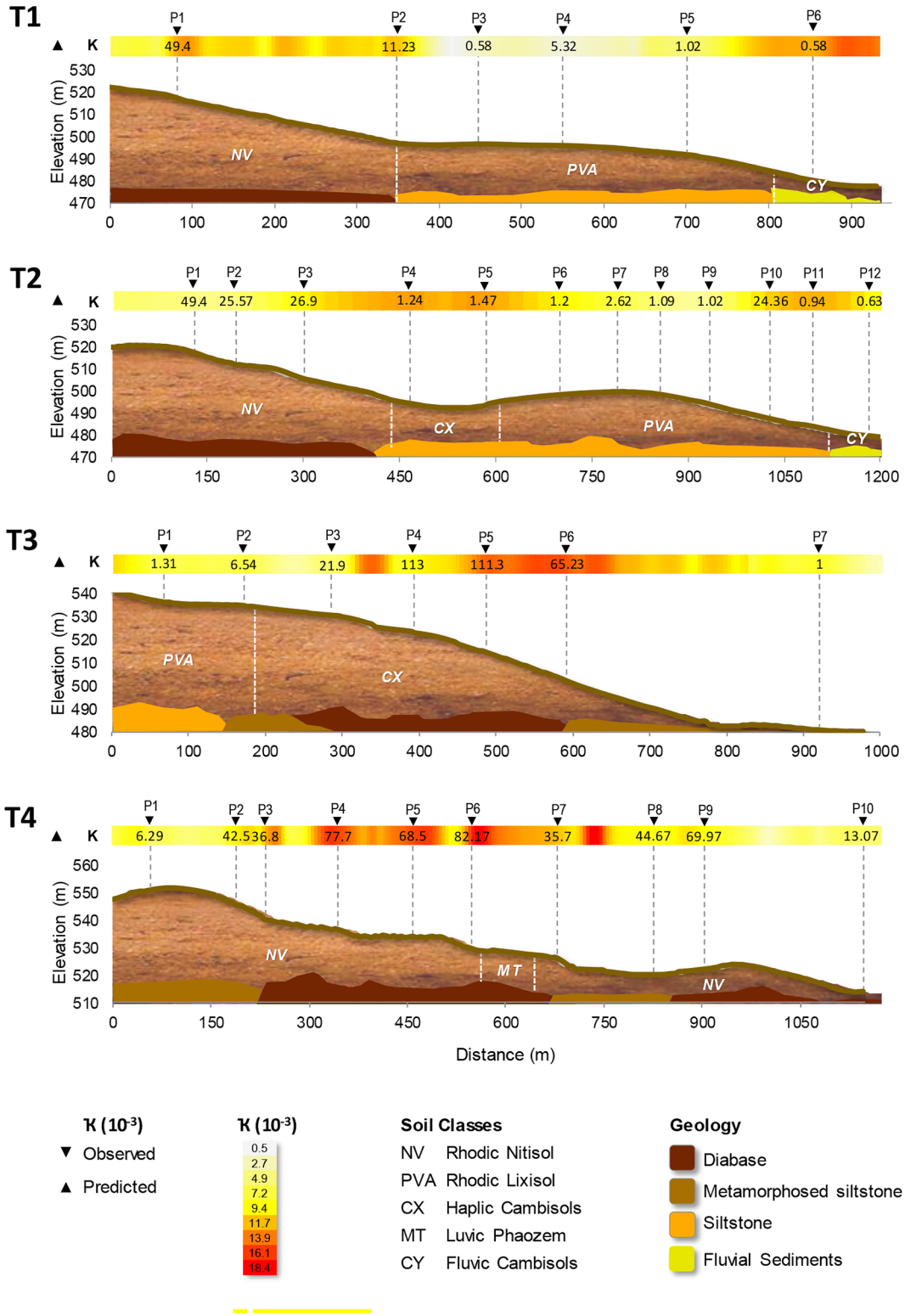

Fig. 4. Magnetic susceptibility κ (× 10^{-3} m^3 kg^{-1}) variability throughout the four topossequences and correspondent soil classes and geological compartment for each collected point. T1: toposequences 1. T2: toposequences 2. T3: toposequences 3. T4: toposequences 4.

and low iron content because lower readings are associated with minerals of low iron content and consequently, more silicate minerals like feldspar, mica and quartz (Hunt et al., 1995). Moreover, according to de Souza Junior et al. (2010), soil κ indicates the presence of ferrimagnetic minerals such as magnetite and maghemite. In addition, according to Santos et al. (2011). Magnetic susceptibility values may indicate evolution of pedogenetic processes in different soil fractions, which may act by decreasing κ if the pedoenvironmental conditions favor the formation of antiferrimagnetic minerals.

In relation to river sediments, the mean value of κ was 6.24 × 10^{-3} m^3 kg^{-1} (Table 1), slightly higher than mean value of siltstone. In fluvial depositional environments, there is a heterogeneous source of magnetic minerals, which explains the increase in κ values in this landscape component which, according to results obtained by Sarmast

et al. (2017), the κ value should decrease with altitude (Ghilardi et al., 2008).

3.2. Magnetic susceptibility variability in toposequences and the effect of altitude on pedogeomorphological processes

In T1 (Fig. 4), an abrupt change in κ values between P2 ($11.23 \times 10^{-3}\ m^3\ kg^{-1}$) and P3 ($0.58 \times 10^{-3}\ m^3\ kg^{-1}$) was observed. This variation is attributed to changes in lithology (diabase/siltstone) and/or soil class Rhodic Nitisol (NV) to Rhodic Lixisol (PVA), because there was little variation in altitude and distance between these points (Fig. 1a). On the other hand, P2 (altitude 496.2 m) consists of a slight depression in relation to neighboring points, and thus is an active depositional site (Fig. 4). Here, the pedogenesis of magnetite and maghemite neoformation is less than the depositional rate of new species, therefore is not enough time to form ferrimagnetic pedogenic minerals.

The neoformation of ferrimagnetic minerals through the release of iron from the source material via weathering and neoformation of secondary minerals via pedogenesis are dependent on the chronology of these processes on geomorphic surfaces (Shenggao, 2000; Spassov et al., 2004; Camargo et al., 2014), and κ can be used to estimate erosion rates (Menshov et al., 2018). Moreover, Curi and Franzmeier (1984), highlighted the importance of geochemical processes in the crystallization of iron oxides, and consequently their κ. Geomorphic surfaces that favor leaching in tropical environments promotes weathering of magnetite and maghemite, resulting in lower values of κ.

Regarding T2 (Fig. 4), the κ values tended to decrease from the upper to the lower parts of the landscape. These results agree with those obtained by De Jong et al. (2000); Blundell et al. (2009) and Sarmast et al. (2017), who analyzed the influence of relief on variability of κ. The variability of κ values is related to the variation of two factors: drainage (Mathé and Lévêque, 2003) and particle transport (Rahimi et al., 2013). The top of the landscape (Fig. 1a) is flatter with deep soil and good infiltration on NV, favoring higher infiltration rates and better drainage. On the other hand, the downstream water flows across the lower parts characterized by CX and PVA, in which shallow and restricted drainage predominates. Grimley and Vepraskas (2000) and Maxbauer et al. (2016), emphasized that for the formation of magnetite and pedogenic maghemite, good drainage conditions are necessary, a fact that occurs mostly at higher altitudes. In addition, Mullins, (1977) and Han and Zhang (2013), stressed that under restricted drainage conditions, the occurrence of a hypoxic environment is favored and, consequently, iron is bio-reduced thus impairing the formation of ferrimagnetic minerals, a fact that would explain the lower values in the lower parts of the toposequence.

De Wispelaere et al. (2015) and Rivas et al. (2006) stated that weak temporary recurrent hydromorphism in some soil classes, resulted in redistribution of Fe-Mn oxides, and this also would contribute to reduction of κ values. At the same time, the transport and redistribution of particles through erosion make minor contributions to κ values because the fine particles tend to be carried out to the watercourse and the sand fraction tends to accumulate in the lower parts of the landscape. This fact helps to explain the lower values of κ in the lower parts of the landscape because ferrimagnetic minerals exist in the sand fraction (Mullins, 1977; Maher and Taylor, 1988; Zhou et al., 1990).

It was observed a significant and positive correlation between κ and altitude ($r = 0.39$, Fig. 5a). Although the results agree with those obtained by De Jong et al. (2000) and Sarmast et al. (2017), they disagree with those obtained by Thompson and Oldfield (1986), who found higher magnetic susceptibility values in the lower parts of the landscape. The most likely explanation is the influence of geology on κ values (Ranganai et al., 2015; Ayoubi et al., 2018).

The representative soil class profiles in different altitudes (Fig. 5b), correspond to the correlation map between κ and the Digital Elevation Model. The relationship between altitude and κ is not always directly proportional. At various points on the map, high κ values were observed in the lower parts of the landscape, resulting in a negative correlation, contrary to results reported in Sarmast et al., (2017). This may be due to the fact that lower altitude areas are in the west over diabase, where the geology and/or pedogenesis exerted the greatest influence on the formation and stability of ferrimagnetic minerals (Lu et al., 2009).

In T3 and T4 (Fig. 4) variations in elevation and relief offer little to explain the variations in κ across the landscape. In T3, significant variations in κ occurred between points P1 and P2, P2 and P3, P5 and P6, and P6 and P7 (Fig. 4), concurrently with changes in lithology, highlighting the transition points between one geological component and another. In T4, the largest variations occurred between points P2 and P3, P6 and P7, P8 and P9, and P9 and P10, also indicating lithological transitions (Fig. 3). These results reaffirm the conclusions of Shenggao, (2000); Vepraskas (2000); Grimley and Hanesch et al. (2007); Camargo et al. (2014); Sarmast et al. (2017) and Ayoubi and Adman (2019), that geology is one of the factors that most affects soil κ . In addition, for certain sites, especially T4 (on NV), pedogenetic processes such as argilluviation may have strongly influenced the κ values in these toposequences (Zhou et al., 1990; Shenggao, 1998; Asgari et al., 2018; Rosowiecka and Nawrocki, 2018). In T3, the predominant soil is CX, with little expression of pedogenesis and great influence by lithology. However, it is difficult to separate which factor (lithology or pedogenesis) most influences κ, as previously reported in Hanesch et al. (2007) who studied the effects of lithology and pedogenesis on κ values in soils of Austria.

3.3. Pedogenesis processes, soil classes and magnetic susceptibility

The highest κ values were found for NV, followed by the CX, both developed on the diabase lithological component (Table 3). Smaller κ values were found for the Fluvic Cambisol (CY) and Rhodic Lixisol (PVA) (Table 3). The mean comparison test (Fig. 3b) demonstrates this difference, where NV and CX belong to the same group and CY and PVA to another. The NV and CX are clayey in texture while CY and PVA are sandy (PVA in the upper layers), which is important for κ values. According to Grimley et al. (2004), soil κ is affected by the soil's surface texture. Thus, processes that lead to clay formation and clay texture, from source materials rich in ferrimagnetic minerals where NV and CX occur, contribute to higher κ values.

The pedogenetic processes that occur in the superficial layers of soil lead to the formation of autogenic ferrimagnetic minerals and exert great influence on κ values. In evolved and weathered soils such as NV, ferrimagnetic minerals are not derived directly from the source material, but through pedogenetic processes such as the secondary neoformation of magnetite and maghemite, which increase κ (Shenggao, 2000; Ayoubi et al., 2018). In addition, ferralitization occurred in this soil type and likely affected the distribution of magnetic minerals in the soil profile, due to accumulation of iron oxides on the soil aggregates (Driessen et al., 2001). On the other hand, in CX soils (clay texture), the ferrimagnetic minerals were derived directly from the parent material and produced the highest κ values (Shenggao, 2000), because this soil is poorly evolved and there is less expression of pedogenesis of secondary ferrimagnetic minerals.

In the PVA (Table 3), the pedogenetic process with the greatest influence on κ values was argilluviation. According to Breemen and Buurman (2003), in PVA soils, translocation of clay from superficial to subsurface layers occurs, so the prevailing surface has a sandy texture and thus lower κ (Ayoubi et al., 2018). These results are corroborated by works of Fine et al. (1992) and Singer and Fine (1989), who reported differences in κ values related to pedogenetic processes such as argilluviation and ferralitization. However, Jordanova et al. (2014) found opposite results in the magnetic behavior in Chernozem profiles in Bulgaria. In CY, the sandy texture prevailed due to the deposition of coarse sediments of different ferrimagnetic materials by the river, which is not related to pedogenesis but rather to depositional processes. In CY, magnetite probably dominates the sand fraction.

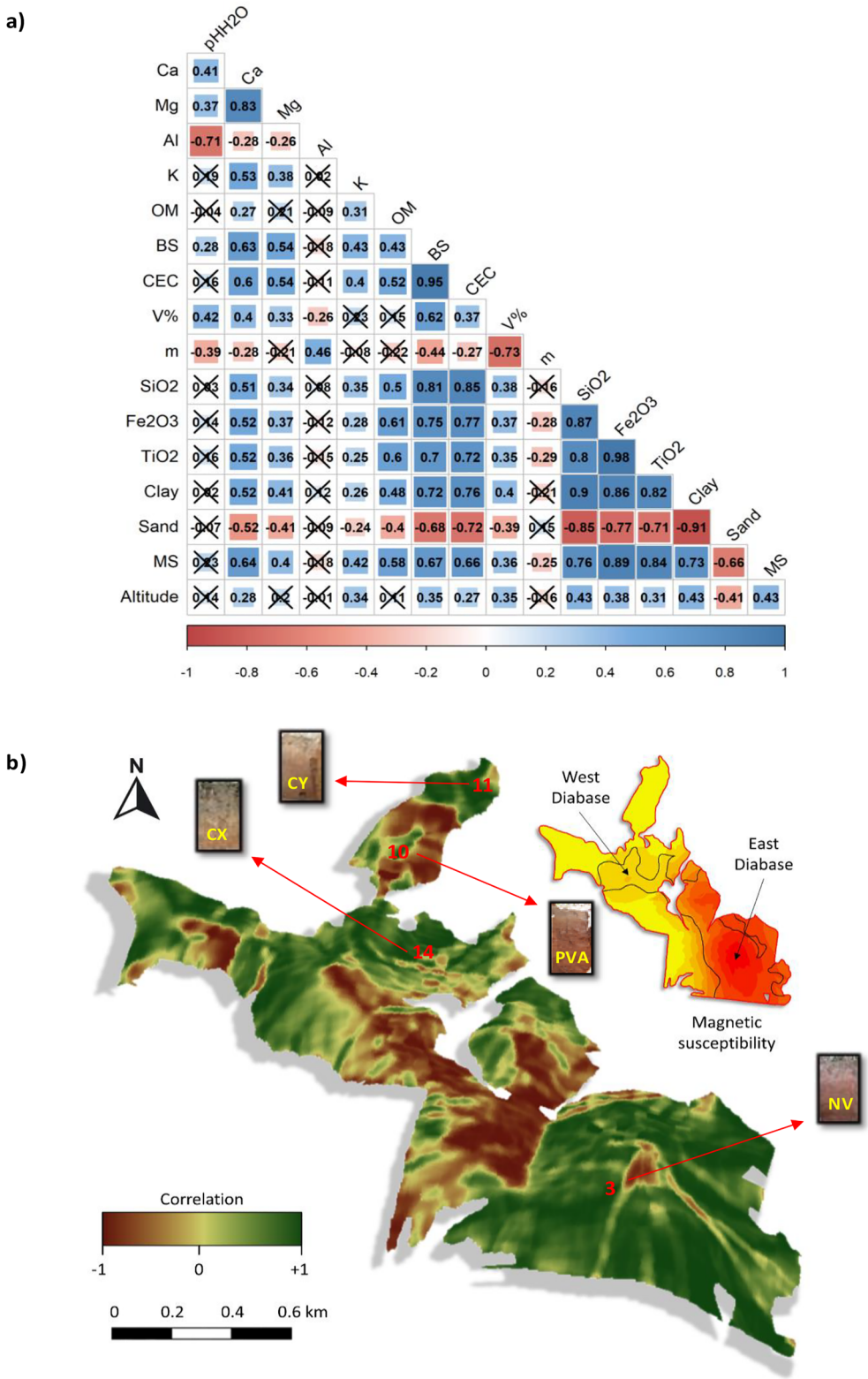

Fig. 5. a) Pearson's correlation coefficient for soil physical and chemical attributes and magnetic susceptibility. Values overlapped with an "X" are not statistically significant at the 0.1 significance level. b) Correlation map between magnetic susceptibility and digital model elevation and representative soil profiles: CX: Haplic Cambisol (soil profile 10), CY: Fluvic Cambisol (soil profile 11), NV: Rhodic Nitisol (soil profile 3): PVA: Rhodic Lixisol (soil profile 10).

Analyzing T1 (between P2 and P3), T2 (between P3 and P4) and T3 (between P2 and P3; and between P6 and P7) (Fig. 4), it is clear that, transitions occur with respect to lithology, soil type, pedogenesis, degree of evolution and texture. Thus κ has a high potential to contribute to identification of transitional boundaries between soil classes, in addition to soil classification and digital soil mapping (Teixeira et al., 2018; Silvero et al., 2019). In fact, Jordanova et al. (2016) used κ data to improve soil classification and field pedological recognition in Bulgarian soils and obtained satisfactory results. Moreover, Marques et al. (2014) separated large groups of soils using κ and concluded that the

Table 3
Descriptive statistics for the analyzed magnetic susceptibility by soil classes.

Summary Statistics	κ (× 10^{-3} m^3 kg^{-1})			
	CX	CY	PVA	NV
Mean	22.96	4.16	2.60	50.94
Standard deviation	33.72	4.95.10	4.86	33.60
Minimum	0.07	0.53	0.35	3.59
Maximum	111.33	14.6	24.36	104.8
Count	11	8	31	21

κ: Magnetic Susceptibility units (× 10^{-3} m^3 kg^{-1}). CX: Haplic Cambisol, CY: Fluvic Cambisol, PVA: Rhodic Lixisol. NV: Rhodic Nitisol.

technique can reproduce the spatial distribution of physical and chemical attributes with high accuracy. Pedogenesis, mainly argilluviation and ferralitization had a greater influence on κ compared to the lithology of more evolved soils, where κ values were higher. These processes acted on variations in ferrimagnetic mineral types in these soil to allow the separation of taxonomic groups. Ayoubi et al. (2018) reached the same conclusion after examining the possibility of stratifying large soil groups in Iran using κ.

3.4. Relationship between soil attributes and magnetic susceptibility

A positive correlation of κ and clay (r = 0.73), as well as κ and iron content (r = 0.89) was found (Fig. 5a). When applied to a regression model (Fig. 6), the same data resulted in a high coefficient of determination for clay (R^2 = 0.62) and iron content (R^2 = 0.79). These results are close to those obtained by Siqueira et al. (2010) for clay (r = 0.68) and iron content (r = 0.82). This correlation was expected because the soils in most of the area are highly weathered and, originated from materials of iron rich origin. For these materials pedogenesis and relief conditions favored the formation and stability of ferrimagnetic minerals through mineral formation of colloidal particles such as maghemite and maghemite (Morgan and Smith, 1981) or ferrihydrite, but not goethite (Michel et al., 2010; Górka-Kostrubiec et al., 2016), mainly in the clay fraction. It is important to realize that magnetite can be present in the clay fraction and thereby increase κ values. Magnetite in the clay fraction can form in soil environments (Taylor et al., 1987) mainly under high temperatures and low oxidizing conditions (Tunstall et al., 1976).

A negative correlation was found for sand and κ (r = -0.66) (Fig. 5a) which may indicate a higher quantity of quartz minerals with low ferrimagnetic mineral contents. In other words, silt and sand fractions tend to have low magnetite content. Despite that, the ferrimagnetic minerals in the sand fraction are more stable than those found in the clay fraction (Han and Zhang, 2013). Siqueira et al. (2010) further explained that surface pedogenic ferrimagnetic minerals may have their κ suppressed by the effects of magnetite crystals in the sand-silt fraction which can be directly oxidized to antiferrimagnetic minerals, thus lowering the κ values (Fabris et al., 1997). In addition, we applied the same data to a regression model and found a lower predictive potential, R^2 = 0.45 (Fig. 6). This result can be attributed to soils with low sand content and consequently higher clay content and thus low κ values. These clayey soils may be a consequence of an environmental condition that did not favor ferrimagnetic minerals.

There was a positive correlation between κ and base saturation (BS) (r = 0.67) (Fig. 5a). These values are concatenated to the correlation values between Ca, Mg and K and κ (r = 0.64, 0.40 and 0.42, respectively). In fact, as exchangeable cations (Ca, Mg and K) increase, the BS value also increases (Kelly et al.,1977). On the other hand, the significant positive correlation between CEC and κ (r = 0.66) (Fig. 5a) is associated with the correlation between clay and κ (r = 0.73). The higher the clay content in the soil, the higher the CEC due to the larger colloid specific surface. There is a tendency for greater amounts of ferrimagnetic minerals (maghemite) to occur in clay fraction originating either from the source material (De Jong et al., 2000) through process of pedogenesis (Ayoubi et al., 2018). In addition, the occurrence of small sub-micron grains of primary magnetite as inclusions within silicate minerals in clay fraction, was observed by Morgan and Smith, (1981). These results are similar to those obtained by Maher (1998) and Siqueira et al. (2010), who reported a positive correlation between κ and CEC, obtaining correlation coefficients of 0.68 and 0.62, respectively.

The significant positive correlation of κ with OM (r = 0.58) (Fig. 5a) was not expected because, according to Schwertmann (1988), high OM levels favor iron complexation and consequently reduce the formation of ferrimagnetic minerals and their precursors. As a result, it tends to form antiferrimagnetic minerals such as goethite if conditions are favorable, as high levels of OM (Schaetzl and Anderson, 2005). These results disagree with those obtained by Ayoubi and Adman (2019), who obtained negative correlation values for soil organic carbon (SOC) and κ, and attributed this fact to the diamagnetic character of OM which reduced the κ. However, Ayoubi et al. (2019) and Górka-Kostrubiec et al. (2016) found positive correlation values between κ and SOC, which can be explained by OM properties that stimulate the pedogenesis of ferromagnetic minerals. Besides, according to Rodríguez Martín et al. (2006), by the higher CEC of OM and high adsorption of some ferrimagnetic minerals. Due to complex comportment of OM, the regression model present low R^2 = 0.28 (Fig. 6).

The magnetic characterization of the soil surface, using geophysical techniques requires low investment, simple execution and high precision. Despite of the sensor detects ferrimagnetic minerals on soil surface, it is possible to infer soil depth attributes and processes, once the processes and environmental factor (as lithology, relief, mineralogy etc.) that affect them is known, which in turn was the purpose of this research.

The understanding of which and how environmental processes in the pedosphere affect the κ in different soil types, can provides information about soil attributes. This information can be used in soil mapping, farming planning, appropriate land use and sustainable management, as well as in digital modeling and map generation.

4. Conclusions

Although the sensor collects the information about the surface, variability in κ across the area was able to identify some transitional areas between map units, mainly with respect to soil texture, which is related to soil class.

With the data obtained through the field sensor, it was possible to reach the same conclusions as the analysis of data produced in the laboratory, without the need to collect, transport and prepare samples. In addition, less time is required to obtain the data.

In this study, the κ of the soils studied exhibited significant correlations between soil texture, CEC and iron content. In addition, the field sensors detected variations in soil κ that allowed us to identify soil classes and lithological variations, thus demonstrating its potential as a tool to discriminate soil great groups and delimit soil types in the soil mapping process.

It was not possible to consider each pedoenvironmental factor in isolation from the soil's κ. Lithology, relief, pedogenesis and geochemical comportment of iron acted concomitantly to determine soil κ.

The lithology and mineralogy of the parent material exerted the greatest influence on κ values in less evolved soil in our study area (CY and CX), while for more evolved soils, ferralitization and argilluviation (NV and PVA, respectively) had the greatest influence.

A large difference was found within the same lithological component located in different geographical positions. Diabase in the eastern presented part of the study area presented higher κ values probably due to different intensities of ferralitization indexes (pedogenic processes), because the area is too small to present significant mineralogical

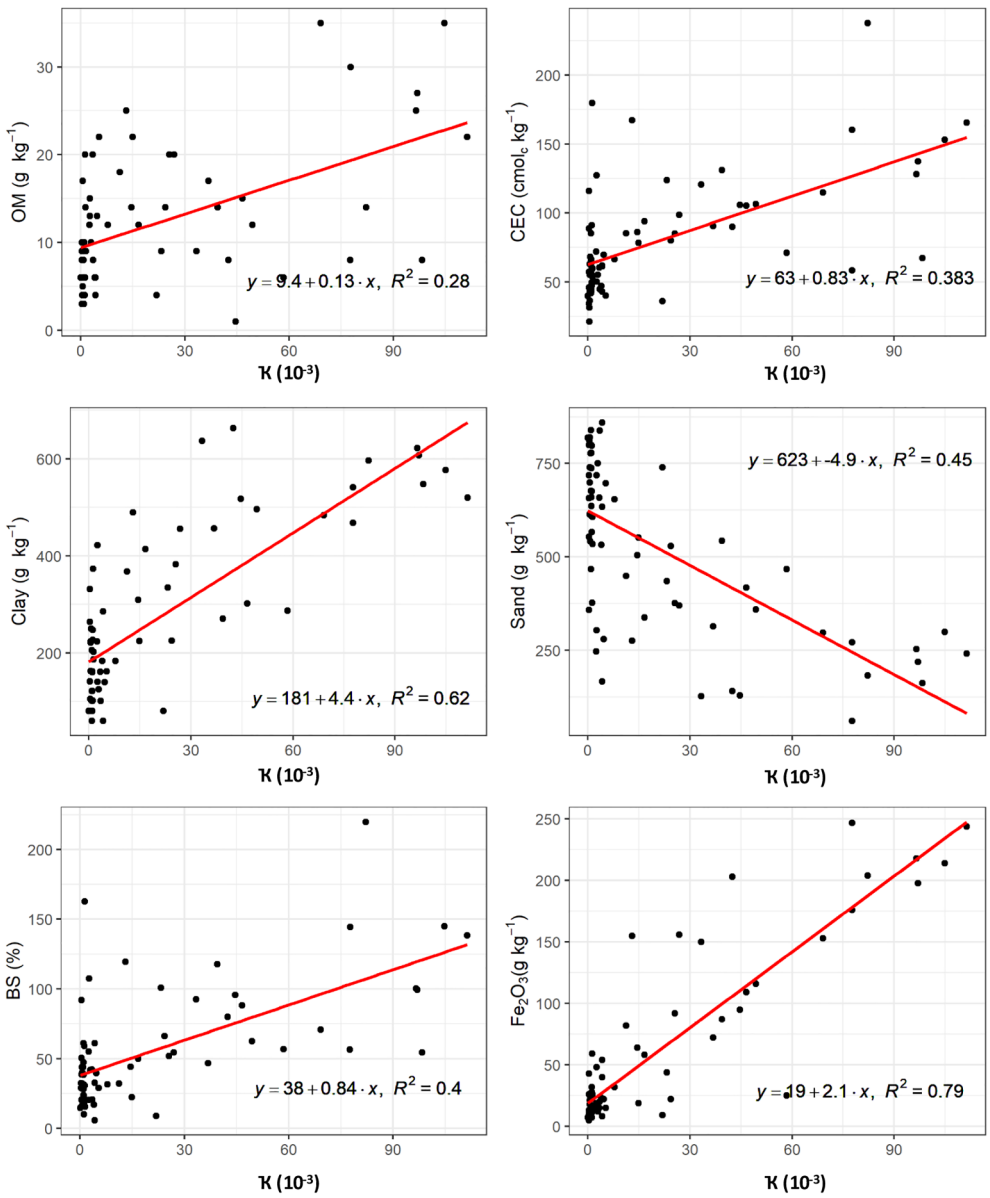

Fig. 6. Regression analysis for (κ) soil magnetic susceptibility ($\times 10^{-3}$ m^3 kg^{-1}) and soil attributes: OM: organic matter; CEC: cation exchange capacity; BS: base saturation. Fe_2O_3 correspond to total iron content.

differences between diabase east and west.

Geomorphological processes work by redistributing ferrimagnetic minerals on the soil surface. Thus, changing soil κ values over time, with a decrease in κ values with altitude. However, in our study area, due to the influence of the west diabase in the lower parts of landscape, the κ values decreased slightly with altitude, with some points showing a slight increase.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2020.114364.

References

Alvares, C.A., Stape, J.L., Sentelhas, P.C., De Moraes Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Zeitschrift 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Asgari, N., Ayoubi, S., Demattê, J.A.M., 2018. Soil drainage assessment by magnetic susceptibility measures in western Iran. Geoderma Reg. 13, 35–42. https://doi.org/

10.1016/j.geodrs.2018.03.003.
Atalay, İ., Saydam, C., Kadir, S., 2018. Pedogeomorphology. In: The Soils of Turkey. Springer, Cham, pp. 75–103.
Aydin, A., Ferré, E.C., Aslan, Z., 2007. The magnetic susceptibility of granitic rocks as a proxy for geochemical composition: Example from the Saruhan granitoids, NE Turkey. Tectonophysics 441, 85–95. https://doi.org/10.1016/j.tecto.2007.04.009.
Ayoubi, S., Abazari, P., Zeraatpisheh, M., 2018. Soil great groups discrimination using magnetic susceptibility technique in a semi-arid region, central Iran. Arab. J. Geosci. 11. https://doi.org/10.1007/s12517-018-3941-4.
Ayoubi, S., Adman, V., 2019. Iron Mineralogy and Magnetic Susceptibility of Soils Developed on Various Rocks in Western Iran. Clays Clay Miner. 67, 217–227. https://doi.org/10.1007/s42860-019-00020-5.
Ayoubi, S., Adman, V., Yousefifard, M., 2019. Use of magnetic susceptibility to assess metals concentration in soils developed on a range of parent materials. Ecotoxicol. Environ. Saf. 168, 138–145. https://doi.org/10.1016/j.ecoenv.2018.10.024.
Ayoubi, S., Mirsaidi, A., 2019. Magnetic susceptibility of Entisols and Aridisols great groups in southeastern Iran. Geoderma Reg. 16, e00202. https://doi.org/10.1016/j.geodrs.2018.e00202.
Bazaglia Filho, O., 2012. Comparação entre mapas de solos obtidos pelos métodos convencional e digital numa área complexa [Comparison between soil maps obtained by conventional and digital methods in complex area]. University of São Paulo, "Luiz de Queiroz". College of Agriculture.
Blundell, A., Dearing, J.A., Boyle, J.F., Hannam, J.A., 2009. Controlling factors for the spatial variability of soil magnetic susceptibility across England and Wales. Earth-Science Rev. 95, 158–188. https://doi.org/10.1016/j.earscirev.2009.05.001.
Breemen van, Nico and Buurman, P., 2003. Soil Formation, 2 nd. ed, Kluwer Academic Publishers. Laboratory of Soil Science and Geology, New YorkK, Boston, Dordrecht, London, Moscow. https://doi.org/10.1017/CBO9781107415324.004.
Brevik, E.C., Calzolari, C., Miller, B.A., Pereira, P., Kabala, C., Baumgarten, A., Jordán, A., 2016. Soil mapping, classification, and pedologic modeling: History and future directions. Geoderma 264, 256–274. https://doi.org/10.1016/j.geoderma.2015.05.017.
Camargo, O.A., Moniz, A.C., Jorge, J.A., Valadares, J.M.A.S., 1986. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico do estado de São Paulo. Bol. técnico 106, 94.
Camargo, L.A., Marques Júnior, J., Pereira, G.T., Bahia, A.S.R. de S., 2014. Clay mineralogy and magnetic susceptibility of Oxisols in geomorphic surfaces. Sci. Agric. 71, 244–256. https://doi.org/10.1590/S0103-90162014000300010.
Cervi, E.C., Maher, B., Poliseli, P.C., de Souza Junior, I.G., da Costa, A.C.S., 2019. Magnetic susceptibility as a pedogenic proxy for grouping of geochemical transects in landscapes. J. Appl. Geophys. 169, 109–117. https://doi.org/10.1016/j.jappgeo.2019.06.017.
Curi, N., Franzmeier, D.P., 1984. Toposequence of Oxisols from the Central Plateau of Brazil. Soil Sci. Soc. Am. J. 48, 341–346. https://doi.org/10.2136/sssaj1984.03615995004800020024x.
Da Costa, A.C.S., Bigham, J.M., Rhoton, F.E., Traina, S.J., 1999. Quantification and characterization of maghemite in soils derived from volcanic rocks in southern Brazil. Clays Clay Miner. 47, 466–473. https://doi.org/10.1346/CCMN.1999.0470408.
Damaceno, J.G., de Castro, D.L., Valcácio, S.N., Souza, Z.S., 2017. Magnetic and gravity modeling of a Paleogene diabase plug in Northeast Brazil. J. Appl. Geophys. 136, 219–230. https://doi.org/10.1016/j.jappgeo.2016.11.006.
De Jong, E., Pennock, D.J., Nestor, P.A., 2000. Magnetic susceptibility of soils in different slope positions in Saskatchewan, Canada. Catena 40, 291–305. https://doi.org/10.1016/S0341-8162(00)00080-1.
De Wispelaere, L., Marcelino, V., Regassa, A., De Grave, E., Dumon, M., Mees, F., Van Ranst, E., 2015. Revisiting nitic horizon properties of Nitisols in SW Ethiopia. Geoderma 243–244, 69–79. https://doi.org/10.1016/j.geoderma.2014.12.021.
Dearing, J.A., 1999. Environmental Magnetic Susceptibility., 2 nd. ed, Using the Bartington MS2 system. Chi Publishing, Kenilworth, UK.
Dearing, J.A., 1994. Environmental magnetic susceptibility, using the Bartington MS2 system.
Dearing, J.A., Hay, K.L., Baban, S.M.J., Huddleston, A.S., Wellington, E.M.H., Loveland, P.J., 1996. Magnetic susceptibility of soil: An evaluation of conflicting theories using a national data set. Geophys. J. Int. 127, 728–734. https://doi.org/10.1111/j.1365-246X.1996.tb04051.x.
Driessen, P., Deckers, J., Spaargaren, O., Nachtergaele, F., 2001. Lecture notes on the major soils of the world, No, 94. ed. World Soil Resources Reports, FAO, Rome.
EMBRAPA, 2017. Manual de metodos de analises, Manual de métodos de análise. de solo.
EMBRAPA, 2011. Documentos 132 Manual de Métodos de. Embrapa 230.
Esri, A.D., 2011. Release 10. Documentation Manual. Environmental Systems Research Institute, Redlands, CA.
Fabris, J.D., De Jesus Filho, M.F., Coey, J.M.D., Mussel, W.D.N., Goulart, A.T., 1997. Iron-rich spinels from Brazilian soils. Hyperfine Interact. 110, 23–32. https://doi.org/10.1023/A:1012619331408.
FAOSTAT, 2003. Food and Agriculture Organization of the United Nations. Statistical Databases.
Fine, P., Singer, M.J., Verosub, K.L., 1992. Use of magnetic-susceptibility measurements in assessing soil uniformity in chronosequence studies. Soil Sci. Soc. Am. J. 56, 1195–1199. https://doi.org/10.2136/sssaj1992.03615995005600040032x.
Foley, J.A., 2011. Can we feed the world sustain the planet? Sci. Am. 305, 60–65.
Ghilardi, M., Kunesch, S., Styllas, M., Fouache, E., 2008. Reconstruction of Mid-Holocene sedimentary environments in the central part of the Thessaloniki Plain (Greece), based on microfaunal identification, magnetic susceptibility and grain-size analyses. Geomorphology 97, 617–630. https://doi.org/10.1016/j.geomorph.2007.09.007.
Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People. Science 327 (5967), 812–818. https://doi.org/10.1126/science:1185383.
Górka-Kostrubiec, B., Teisseyre-Jeleńska, M., Dytłow, S.K., 2016. Magnetic properties as indicators of Chernozem soil development. Catena 138, 91–102. https://doi.org/10.1016/j.catena.2015.11.014.
Govedarica, D.D., Gavrilov, M.B., Zeremski, T.M., Govedarica, O.M., Hambach, U., Tomić, N.A., Sentić, I., Marković, S.B., 2019. Relationships between heavy metal content and magnetic susceptibility in road side loess profiles: A possible way to detect pollution. Quat. Int. 502, 148–159. https://doi.org/10.1016/j.quaint.2018.01.020.
GRANT, U.S., 1900. Contact metamorphism of a basic igneous rock. Geol. Soc. Am. Bull. 11, 503–510. https://doi.org/10.1130/gsab-11-503.
Grimley, D.A., Arruda, N.K., Bramstedt, M.W., 2004. Using magnetic susceptibility to facilitate more rapid, reproducible and precise delineation of hydric soils in the midwestern USA. Catena 58, 183–213. https://doi.org/10.1016/j.catena.2004.03.001.
Grimley, D.A., Vepraskas, M.J., 2000. Magnetic Susceptibility for Use in Delineating Hydric Soils. Soil Sci. Soc. Am. J. 64, 2174–2180. https://doi.org/10.2136/sssaj2000.6462174x.
Grison, H., Petrovsky, E., Kapicka, A., Stejskalova, S., 2016. Magnetic and chemical parameters of andic soils and their relation to selected pedogenesis factors. Catena 139, 179–190. https://doi.org/10.1016/j.catena.2015.12.005.
Grunwald, S., Thompson, J.A., Boettinger, J.L., 2011. Digital Soil Mapping and Modeling at Continental Scales: Finding Solutions for Global Issues. Soil Sci. Soc. Am. J. 75, 1201–1213. https://doi.org/10.2136/sssaj2011.0025.
Han, G.Z., Zhang, G.L., 2013. Changes in magnetic properties and their pedogenetic implications for paddy soil chronosequences from different parent materials in south China. Eur. J. Soil Sci. 64, 435–444. https://doi.org/10.1111/ejss.12050.
Hanesch, M., Rantitsch, G., Hemetsberger, S., Scholger, R., 2007. Lithological and pedological influences on the magnetic susceptibility of soil: Their consideration in magnetic pollution mapping. Sci. Total Environ. 382, 351–363. https://doi.org/10.1016/j.scitotenv.2007.04.007.
Hooper, R.L., 1987. Factors affecting the magnetic susceptibility of baked rocks above a burned coal seam. Int. J. Coal Geol. 9, 157–169.
Hu, P., Heslop, D., Viscarra Rossel, R.A., Roberts, A.P., Zhao, X., 2020. Continental-scale magnetic properties of surficial Australian soils. Earth-Science Rev. 203, 103028. https://doi.org/10.1016/j.earscirev.2019.103028.
Hunt, Christopher P, M.B.M. and B.S.K., 1995. Magnetic Properties of Rocks and Minerals, in: Ahrens, T.J. (Ed.), Rock Physics & Phase Relations A Handbook of Physical Const. American Geophysical Union, Washington, pp. 189–196.
IUSS Working Group WRB, 2015. World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps, World Soil Resources Reports No. 106. https://doi.org/10.1017/S0014479706394902.
Quaggio, J.A., Raij, B., 2001. Determination of pH in calcium chloride and total acidity. Chem. Anal. Fertil. Eval. Trop. Soils. Inst. Agronômico Campinas Campinas, 181–188.
Jiménez, C., Benavides, J., Ospina-Salazar, D.I., Zúñiga, O., Ochoa, O., Mosquera, C., 2017. 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. Cauca. Rev. Cienc. Agri 34, 33–45. https://doi.org/10.22267/rcia.173402.70.
Jordanova, D., Jordanova, N., Petrov, P., 2014. Pattern of cumulative soil erosion and redistribution pinpointed through magnetic signature of Chernozem soils. Catena 120, 46–56. https://doi.org/10.1016/j.catena.2014.03.020.
Jordanova, N., 2016. Soil Magnetism: Applications in Pedology. Academic Press, Environmental Science and Agriculture.
Jordanova, N., Jordanova, D., Mokreva, A., Ishlyamski, D., Georgieva, B., 2019. Temporal changes in magnetic signal of burnt soils – A compelling three years pilot study. Sci. Total Environ. 669, 729–738. https://doi.org/10.1016/j.scitotenv.2019.03.173.
Jordanova, N., Jordanova, D., Petrov, P., 2016. Soil magnetic properties in Bulgaria at a national scale-Challenges and benefits. Glob. Planet. Change 137, 107–122. https://doi.org/10.1016/j.gloplacha.2015.12.015.
Kanu, M.O., Meludu, O.C., Basavaiah, N., Oniku, A.S., 2019. Relationship between mineral magnetic properties and soil textural parameters. Acta Geophys. 67, 517–532. https://doi.org/10.1007/s11600-019-00248-8.
J.M., Resources, N., Lafayette, W., 1977. Acid precipitation effects on soil pH and base saturation of exchangeable sites 1, 401–408.
Borgne, Le, 1960. Influence du few sur les propriétiés magnétiques du sol et du granite. Ann. Geophys. 16, 159–195.
Borgne, Le, 1955. Susceptibilité magnétique anormal de sol superficial. Ann. Geophys. 11, 399–419.
Li, J., Heap, A.D., 2008. A Review of Spatial Interpolation Methods for Environmental Scientists. Aust. Geol. Surv. Organ. GeoCat# 68, 154.
Lim, C.H., Jackson, M.L., 1986. Dissolution for total elemental analysis, in: Madison (Ed.), Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties. American Society of Agronomy, pp. 1–12.
Lourenço, A.M., Sequeira, E., Sant'Ovaia, H., Gomes, C.R., 2014. Magnetic, geochemical and pedological characterisation of soil profiles from different environments and geological backgrounds near Coimbra, Portugal. Geoderma 213, 408–418. https://doi.org/10.1016/j.geoderma.2013.07.035.
Lu, S., Wang, H., Bai, S., 2009. Heavy metal contents and magnetic susceptibility of soils along an urban - Rural gradient in rapidly growing city of eastern China. Environ. Monit. Assess. 155, 91–101. https://doi.org/10.1007/s10661-008-0420-5.
Maher, B.A., 1998. Magnetic properties of modern soils and quaternary loessic paleosols: Paleoclimatic implications. Palaeogeogr. Palaeoclimatol. Palaeoecol. 137, 25–54. https://doi.org/10.1016/S0031-0182(97)00103-X.

Maher, B.A., Alekseev, A., Alekseeva, T., 2003. Magnetic mineralogy of soils across the Russian Steppe: Climatic dependence of pedogenic magnetite formation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 201, 321–341. https://doi.org/10.1016/S0031-0182(03)00618-7.

Maher, B.A., Taylor, R.M., 1988. Formation of ultrafine-grained magnetite in soils. Nature 336, 368–370. https://doi.org/10.1038/336368a0.

Marques, J., Siqueira, D.S., Camargo, L.A., Teixeira, D.D.B., Barrón, V., Torrent, J., 2014. Magnetic susceptibility and diffuse reflectance spectroscopy to characterize the spatial variability of soil properties in a brazilian haplustalf. Geoderma 219–220, 63–71. https://doi.org/10.1016/j.geoderma.2013.12.007.

Mathé, V., Lévêque, F., 2003. High resolution magnetic survey for soil monitoring: Detection of drainage and soil tillage effects. Earth Planet. Sci. Lett. 212, 241–251. https://doi.org/10.1016/S0012-821X(03)00241-3.

Maxbauer, D.P., Feinberg, J.M., Fox, D.L., 2016. Magnetic mineral assemblages in soils and paleosols as the basis for paleoprecipitation proxies: A review of magnetic methods and challenges. Earth-Science Rev. 155, 28–48. https://doi.org/10.1016/j.earscirev.2016.01.014.

McFadden, M., Scott, W.R., 2013. Broadband soil susceptibility measurements for EMI applications. J. Appl. Geophys. 90, 119–125. https://doi.org/10.1016/j.jappgeo.2013.01.009.

Menshov, O., Kruglov, O., Vyzhva, S., Nazarok, P., Pereira, P., Pastushenko, T., 2018. Magnetic methods in tracing soil erosion, Kharkov Region. Ukraine. Stud. Geophys. Geod. 62, 681–696. https://doi.org/10.1007/s11200-018-0803-1.

Michel, F.M., Barrón, V., Torrent, J., Morales, M.P., Serna, C.J., Boily, J.F., Liu, Q., Ambrosini, A., Cismasu, A.C., Brown, G.E., 2010. Ordered ferrimagnetic form of ferrihydrite reveals links among structure, composition, and magnetism. Proc. Natl. Acad. Sci. U. S. A. 107, 2787–2792. https://doi.org/10.1073/pnas.0910170107.

Mokhtari Karchegani, P., Ayoubi, S., Lu, S.G., Honarju, N., 2011. Use of magnetic measures to assess soil redistribution following deforestation in hilly region. J. Appl. Geophys. 75, 227–236. https://doi.org/10.1016/j.jappgeo.2011.07.017.

Morgan, G.E., Smith, P.P.K., 1981. Transmission electron microscope and rock magnetic investigations of remanence carriers in a Precambrian metadolerite. Earth Planet. Sci. Lett. 53, 226–240. https://doi.org/10.1016/0012-821X(81)90156-4.

Mullins, C.E., 1977. Magnetic Susceptibility of the Soil and Its Significance in Soil Science – a Review. J. Soil Sci. 28, 223–246. https://doi.org/10.1111/j.1365-2389.1977.tb02232.x.

Paisani, J.C., Pontelli, M.E., de Barros Corrêa, A.Ô.C., Rech Rodrigues, R.A., 2013. Pedogeochemistry and micromorphology of oxisols - A basis for understanding etchplanation in the Araucárias Plateau (Southern Brazil) in the Late Quaternary. J. South Am. Earth Sci. 48, 1–12. https://doi.org/10.1016/j.jsames.2013.07.011.

Taylor, R. M., B. A. Maher, P.G.S., 1987. Magnetite is single-domain soils: I. The synthesis of and superparamagnetic magnetite. Clay Miner. 22, 411–422. https://doi.org/doi:10.1180/claymin.1987.022.4.05.

Core Team, R., 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rachwał, M., Kardel, K., Magiera, T., Bens, O., 2017. Application of magnetic susceptibility in assessment of heavy metal contamination of Saxonian soil (Germany) caused by industrial dust deposition. Geoderma 295, 10–21. https://doi.org/10.1016/j.geoderma.2017.02.007.

Rahimi, M.R., Ayoubi, S., Abdi, M.R., 2013. Magnetic susceptibility and Cs-137 inventory variability as influenced by land use change and slope positions in a hilly, semiarid region of west-central Iran. J. Appl. Geophys. 89, 68–75. https://doi.org/10.1016/j.jappgeo.2012.11.009.

Ranganai, R.T., Moidaki, M., King, G.J., 2015. Magnetic Susceptibility of Soils from Eastern Botswana: A Reconnaissance Survey and Potential Applications. J. Geogr. Geol. 7, 45. https://doi.org/10.5539/jgg.v7n4p45.

Rivas, J., Ortega, B., Sedov, S., Solleiro, E., Sychera, S., 2006. Rock magnetism and pedogenetic processes in Luvisol profiles: Examples from Central Russia and Central Mexico. Quat. Int. 156–157, 212–223. https://doi.org/10.1016/j.quaint.2006.05.007.

Robinson, D.A., Panagos, P., Borrelli, P., Jones, A., Montanarella, L., Tye, A., Obst, C.G., 2017. Soil natural capital in Europe; A framework for state and change assessment. Sci. Rep. 7, 1–14. https://doi.org/10.1038/s41598-017-06819-3.

Rochette, P., Jackson, M., Aubourg, C., 1992. Rock magnetism andn the interpretation of magnetic susceptibility. Rev. Geophys. 30, 209–226.

Rodríguez Martín, J.A., Arias, M.L., Grau Corbí, J.M., 2006. Heavy metals contents in agricultural topsoils in the Ebro basin (Spain). Application of the multivariate geoestatistical methods to study spatial variations. Environ. Pollut. 144, 1001–1012. https://doi.org/10.1016/j.envpol.2006.01.045.

Roman, S.A., Johnson, W.C., Geiss, C.E., 2013. Grass fires-an unlikely process to explain the magnetic properties of prairie soils. Geophys. J. Int. 195, 1566–1575. https://doi.org/10.1093/gji/ggt349.

Rosowiecka, O., Nawrocki, J., 2018. Magnetic Vertical Structure of Soil as a Result of Transformation of Iron Oxides During Pedogenesis. The Case Study of Soil Profiles from Slovakia and Ukraine. Magnetometry. Environ. Sci. 103–125. https://doi.org/10.1007/978-3-319-60213-4.

Samuel-Rosa, A., Dalmolin, R.S.D., Moura-Bueno, J.M., Teixeira, W.G., Alba, J.M.F., 2020. Open legacy soil survey data in Brazil: Geospatial data quality and how to improve it. Sci. Agric. 77, 1–11. https://doi.org/10.1590/1678-992x-2017-0430.

Santos, H.L., Júnior, J.M., Matias, S.S.R., Siqueira, D.S., Pereira, G.T., 2011. Suscetibilidade magnética na identificação de compartimentos da paisagem em uma vertente. Rev. Bras. Ciencias Agrar. 6, 710–716. https://doi.org/10.5039/agraria.v6i4a1347.

Santoso, N.A., Iqbal, M., Ekawati, G., Firdaus, R., 2019. Study of pH and Magnetic Susceptibility to Fertility Rate of Agricultural Soil around Institut Teknologi Sumatera, Lampung, Indonesia. IOP Conf. Ser. Earth Environ. Sci. 258, 12001. https://doi.org/10.1088/1755-1315/258/1/012001.

Sarmast, M., Farpoor, M.H., Esfandiarpour Boroujeni, I., 2017. Magnetic susceptibility of soils along a lithotoposequence in southeast Iran. Catena 156, 252–262. https://doi.org/10.1016/j.catena.2017.04.019.

Sawyer, E.W., 1986. The influence of source rock type, chemical weathering and sorting on the geochemistry of clastic sediments from the Quetico Metasedimentary Belt, Superior Province. Canada. Chem. Geol. 55, 77–95. https://doi.org/10.1016/0009-2541(86)90129-4.

Schaetzl, J Randall, Anderson, S., 2005. Soil Genesis and Geomorphology. Cambridge University Press, New York.

Schwertmann, U., 1988. Occurrence and formation of iron oxides in various pedoenvironments. Iron soils clay Miner. 267–308. https://doi.org/10.1007/978-94-009-4007-9_11.

Shenggao, L., 2000. Lithological factors affecting magnetic susceptibility of subtropical soils, Zhejiang Province, China. Catena 40, 359–373. https://doi.org/10.1016/S0341-8162(00)00092-8.

Shenggao, L., 1998. Magnetic properties and iron oxide mineralogy of subtropical soils and environmental implications. Zhejiang University, China.

Silvero, N.E.Q., Siqueira, D.S., Coelho, R.M., Da Costa Ferreira, D., Marques, J., 2019. Protocol for the use of legacy data and magnetic signature on soil mapping of São Paulo Central West. Brazil. Sci. Total Environ. 693. https://doi.org/10.1016/j.scitotenv.2019.07.269.

Singer, M.J., Fine, P., 1989. Pedogenic factors affecting magnetic susceptibility of northern California soils. Soil Sci. Soc. Am. J. 53, 1119–1127. https://doi.org/10.2136/sssaj1989.03615995005300040023x.

Singer, M.J., Verosub, K.L., Fine, P., TenPas, J., 1996. A conceptual model for the enhancement of magnetic susceptibility in soils. Quat. Int. 34–36, 243–248. https://doi.org/10.1016/1040-6182(95)00089-5.

Siqueira, D.S., Marques, J., Matias, S.S.R., Barrón, V., Torrent, J., Baffa, O., Oliveira, L.C., 2010. Correlation of properties of Brazilian Haplustalfs with magnetic susceptibility measurements. Soil Use Manag. 26, 425–431. https://doi.org/10.1111/j.1475-2743.2010.00294.x.

Smith, R.C., Rose, A.W., 1975. Geology and Geochemistry of Triassic Diabase in Pennsylvania. Bull. Geol. Soc. Am. 86, 943–955. https://doi.org/10.1130/0016-7606(1975)86<943:GAGOTD>2.0.CO;2.

Souza Junior, I.G. de, Costa, A.C.S. da, Vilar, C.C., Hoepers, A., 2010. Mineralogia e susceptibilidade magnética dos óxidos de ferro do horizonte B de solos do Estado do Paraná. Ciência Rural 40, 513–519. https://doi.org/10.1590/s0103-84782010000300003.

Spassov, S., Egli, R., Heller, F., Nourgaliev, D.K., Hannam, J., 2004. Magnetic quantification of urban pollution sources in atmospheric particulate matter. Geophys. J. Int. 159, 555–564. https://doi.org/10.1111/j.1365-246X.2004.02438.x.

Su, N., Yang, S.Y., Wang, X.D., Bi, L., Yang, C.F., 2015. Magnetic parameters indicate the intensity of chemical weathering developed on igneous rocks in China. Catena 133, 328–341. https://doi.org/10.1016/j.catena.2015.06.003.

Teixeira, D.D.B., Marques, J., Siqueira, D.S., Vasconcelos, V., Carvalho, O.A., Martins, É.S., Pereira, G.T., 2018. Mapping units based on spatial uncertainty of magnetic susceptibility and clay content. Catena 164, 79–87. https://doi.org/10.1016/j.catena.2017.12.038.

Thompson, Roy, Oldfield, Frank (Eds.), 1986. Environmental Magnetism. Springer Netherlands, Dordrecht.

Tunstall, B.R., Martin, T.J., Walker, J., Gill, A.M., Aston, A.R., 1976. Soil temperatures induced by an experimental log pile fire: preliminary data analysis. L. use Res. - Camberra Technical, CSIRO Div.

Valaee, M., Ayoubi, S., Khormali, F., Lu, S.G., Karimzadeh, H.R., 2016. Using magnetic susceptibility to discriminate between soil moisture regimes in selected loess and loess-like soils in northern Iran. J. Appl. Geophys. 127, 23–30. https://doi.org/10.1016/j.jappgeo.2016.02.006.

Van Dam, R.L., Hendrickx, J.M., Harrison, B., Borchers, B., Norman, D.I., Ndur, S., Jasper, C., Niemeyer, P., Nartey, R., Vega, D.N., Calvo, L., Simms, J.E., 2004. Spatial variability of magnetic soil properties. Detect. Remediat. Technol. Mines Minelike Targets IX 5415, 665. https://doi.org/10.1117/12.540693.

Walkley, A., 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 Sci. 37, 29–38.

Yurtseven-Sandker, A., Cioppa, M.T., 2016. Tracking the Historical Traces of Soil Pollution from an Iron-Sintering Plant by Using Magnetic Susceptibility in Wawa, Ontario. Canada. Water. Air. Soil Pollut. 227. https://doi.org/10.1007/s11270-016-3140-4.

Zhou, L.P., Oldfield, F., Wintle, A.G., Robinson, S.G., Wang, J.T., 1990. Partly pedogenic origin of magnetic variations in Chinese loess. Nature 346, 737–739. https://doi.org/10.1038/346737a0.