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Sample planning for quantifying and mapping magnetic susceptibility, clay content, and base saturation using auxiliary information

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ABSTRACT

There is a great global demand for detailed soil property description; therefore, an ideal site-specific sampling has become indispensable to meet this demand. This study aimed to assess the implications of incorporating geological, geomorphological, and pedological information in reducing the required sampling density for magnetic susceptibility (MS), clay content (CC), and base saturation (BS) characterizations. The study area is located in Guatapará-SP (Brazil) and has 870 ha. A total of 371 samples were collected at a depth of 0–0.25 m for assessing magnetic susceptibility (MS), clay content, and base saturation (BS). A density of one sample was considered every 2.6, 3, 4, 5, 6, 7, 8, 9, 11, and 14 ha. The incorporation of secondary information in a geostatistical framework was performed by means of simple kriging with varying local means. Accuracy assessment of the spatial estimates at each sampling density, with and without incorporating secondary information, was performed by using external validation. For MS, geology and geomorphology information were responsible for about 45% and 44% spatial continuity, respectively. As for CC, these results were higher, being of 54% (geology) and 53% (geomorphology). Conversely, no spatial variability was detected for these properties by using pedological information. For BS, there was no relationship between secondary information and its spatial continuity. Incorporating geological and geomorphological information to MS data enabled a reduction in the number of samples required of 37% and 44%, respectively, in order to represent its spatial pattern. Likewise, this information provides a 35% reduction in the required sampling density for CC. However, secondary information was no helpful in decreasing sampling density for BS. In brief, incorporating pre-existing information can ensure a high quality of estimates and decrease the number of samples required for a detailed description for both MS and CC. Estimates of spatial patterns with geological and geomorphological information for modeling of soil properties might have a greater potential of use for environmental model composition.

1. Introduction

Recent changes in land use and intensification of formation and degradation processes have compromised soil and environment quality. In this context, there is a great demand for detailed information about soil in order to perform a sustainable management (Grunwald et al., 2011; Brevik et al., 2016; Hengl et al., 2017). Soil mapping is one of the key tools to meet this demand and as a strategic planning of agricultural, urban, and management activities of soil variability (Li and Heap, 2008). Once at the level of detail required (Delden et al., 2011), soil maps can be used for delineating areas with deficiency or toxicity of a particular chemical element (Chen et al., 2016). Besides, these maps highlight the relationship between soil properties and agricultural productivity, animal production, and human health (White and Zasoski, 1999; Siqueira et al., 2016), besides playing a key role in optimization of sampling plans (Vašát et al., 2010; Montanari et al., 2012) and agricultural inputs (White and Zasoski, 1999).

Several protocols for soil modeling and mapping have been developed to assist the understanding of its variability (Minasny and McBratney, 2016). According to Castrignanò et al. (2009), the main

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methodologies used can be divided into two groups: (i) protocols that consider the soil as a discontinuous unit, in which is possible its division into a discrete number of classes; and (ii) protocols that consider the soil as a continuous body, which quantitatively describe the variation of variables in space. The first is represented mainly by mapping methodologies by the similarity between pedons (Soil Survey Staff, 1975), in addition to free and categorical mappings, in which concepts of soil-landscape relationship are used (Hudson, 1992). The second is represented mainly by mappings using geostatistical analysis (Oliver and Webster, 2014).

However, when considering the soil as a continuous body, several researchers have observed that the variability of its properties matches the geological variation (Liu et al., 2013; Siqueira et al., 2014), relief form (Siqueira et al., 2010; Quijano et al., 2011; Camargo et al., 2016), and agricultural management practices (Liu et al., 2013). Thus, hybrid mapping protocols, in which both concepts are brought together, have stood out for the last decade, especially for studies on local and regional scales (McBratney et al., 2000). In addition, hybrid mapping techniques are commonly used in other areas such as geological mapping, in which information from soil maps on detailed scales can be used to construct more accurate geological maps than the traditional method (Brevik and Miller, 2015).

In these protocols, previously acquired information such as geological, geomorphological, or pedological maps, or even property maps, on less detailed scales, can be used along with quantitative analyses (e.g. geostatistical analysis) to refine the mapping units and increase the understanding and reliability of the spatial patterns (Castrignanò et al., 2009; Cambule et al., 2013; Hengl et al., 2014, 2017; Vasques et al., 2016).

For constructing and delineating these soil maps, sample planning by means of identifying the appropriate sampling density presents an important stage to be assessed (McBratney et al., 2002; Vašát et al., 2010; Siqueira et al., 2014). Sampling density directly influences the level of detail to be obtained (scale or resolution) (Delden et al., 2011) and mapping costs (Demattê et al., 2007). Measures such as the Shannon diversity index (Minasny et al., 2010) can be used as the first indication of soil pedodiversity intensity (variability) at large scales. For more detailed scales (regional or local), the study of incorporation of secondary information into geostatistical models (Castrignanò et al., 2009; Cambule et al., 2013; Vasques et al., 2016) and use of properties with potential for identifying the variation of soil formation processes (magnetic susceptibility–MS, electrical conductivity, and diffuse reflectance spectroscopy) (Bilgili et al., 2011; Siqueira et al., 2014; Mirzaeitalarposhti et al., 2017) represent an increasing research activity. However, the secondary information often used have quantitative (satellite information, electrical conductivity, and MS) (Benedetto et al., 2012) and non-qualitative or categorical nature (Castrignanò et al., 2009).

Qualitative information, which is often available at no charge, has a great potential to integrate sample planning of soil properties (Cambule et al., 2013). However, one of the main difficulties is the definition of what information should be used for the sample planning and mapping of soil properties (Miller et al., 2015). Hengl et al. (2014) state that information on climate, lithology, biomass indexes and taxonomic units are the main covariates for modeling soil properties on a global scale. For regional and local scales, information on geomorphology, lithology, and pedology present a great potential (Anderson et al., 2003; Vasques et al., 2016). The hypothesis of this research is that the knowledge on soil formation factors (geology and landscape shape), often previously mapped and available at no charge, should be considered at the time of mathematical modeling. Its incorporation may assist in delineating spatial patterns of soil properties, as well as reducing the required sampling density for representing the phenomenon under study. In this sense, this study aimed to assess the incorporation of geological, geomorphological, and pedological information in reducing the required sampling density for characterizing magnetic susceptibility, clay content, and base saturation.

2. Materials and methods

2.1. Description of the area and sampling

The study area was located in Guatapará, São Paulo State, Brazil (Fig. 1a). Its central coordinates are 21°28′40″S and 48°01′38″W, with an altitude ranging from 649 to 519 m. According to Thornthwaite (1948), the local climate can be defined as B1rB′4a′, which means a humid mesothermal climate with small water deficit and summer evapotranspiration lower than 48% of the annual evapotranspiration. The local natural vegetation consisted of a tropical semideciduous forest. Currently, the area is cultivated with sugarcane under mechanized harvesting system for over 10 years.

The area has three parent materials related to the transition between the Basalt of the São Bento Group, Serra Geral Formation (SG), Eluvial-Colluvial Deposit (ECD), and Alluvial Deposit (AD) (IPT – Instituto de Pesquisas Tecnológicas do Estado de São Paulo, 1981; GEOBANK, 2014) (Fig. 1b). Technical visits were carried out in the area in order to verify the geological information. Geomorphometric compartments were identified according to the methodology proposed by

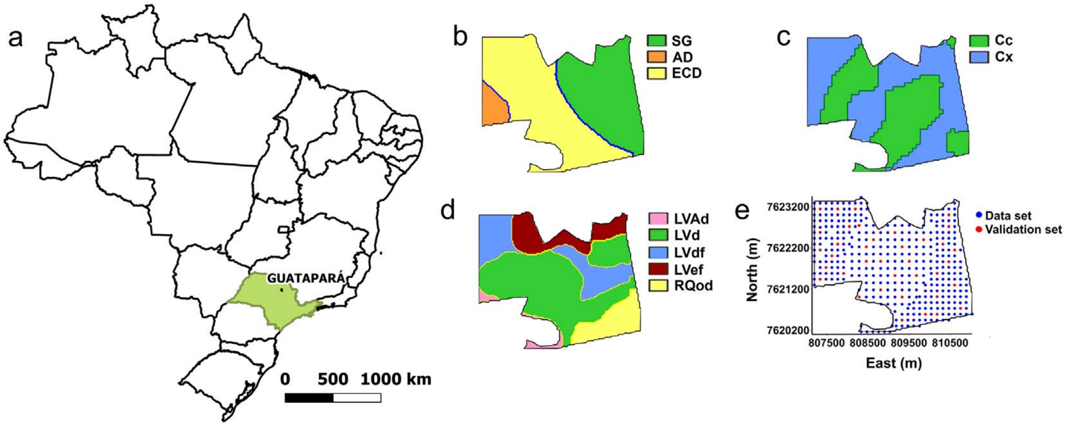

Fig. 1. Characterization of the study area. Location of the sampling area (a); geological map at scale 1:500,000 (SG–Serra Geral; AD–Alluvial Deposit; ECD–Eluvial-Colluvial Deposit) (b); geomorphometric map at scale 1:100,000 (Cc–concave; Cx–convex) (c); pedological map at scale 1:12,000 (LVAd (SiBCS: *Latossolo Vermelho-Amarelo distrófico com textura média*; Soil Taxonomy: Typic Hapludox); LVd (SiBCS: *Latossolo Vermelho distrófico com textura média*; Soil Taxonomy: Typic Hapludox); LVdf (SiBCS: *Latossolo Vermelho distroférrico com textura argilosa*; Soil Taxonomy: Typic Hapludox); LVef (SiBCS: *Latossolo Vermelho eutroférrico com textura argilosa*; Soil Taxonomy: Typic Eutrudox); RQod (SiBCS: *Neossolo Quartzarênico órtico distrófico com textura arenosa*; Soil Taxonomy: Typic Quartzipsamment)) (d); spatial distribution of samples (e).