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Visual analysis and X-ray computed tomography for assessing the spatial variability of soil structure in a cultivated Oxisol

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ABSTRACT

Intensive agriculture and its associated practices modify soil structure, aiming to enhance conditions for root growth. However, there are also negative consequences on many soil properties which vary with many factors, including soil depth and evaluation techniques. This study aimed to assess the effects of soil management in coffee plantations on soil structure and its spatial variability, as influenced by soil depth and time elapsed since mechanical cultivation and planting (3 or 6 yrs) on a clayey Oxisol in Minas Gerais, Brazil. Two contrasting techniques were used: in-field, expedite visual analysis of crop profiles, and X-ray computed tomography (CT) scanning of undisturbed cores at three depths (20–34, 80–94, and 150–164 cm), the latter producing X-ray attenuation data further processed by geostatistical tools. For both stand ages, visual analysis in field showed the soil structure at 20–34 cm layer as similarly loose. The semivariograms elaborated from X-ray CT attenuation values in grayscale for three directions X, Y (horizontal) and Z (vertical), showed increased spatial variability, especially in the horizontal directions. In deeper layers, the two techniques showed results varying with stand age, depth of soil preparation, root development and soil formation processes. For instance, the 80–94 cm layer was marked by visually distinct clods, with narrower prediction intervals for semivariograms in all directions when compared to the other depths, suggesting a low spatial variability. The joint use of the two techniques has allowed not only the validation of an expedite method of soil structure evaluation, but also a more detailed perspective on how the spatial variability varies across soil depth and time of soil use.

1. Introduction

Agricultural management affects soil structure with different intensity according to factors such as site preparation, time of cultivation, depth and climatic zone, among others. The spatial organization of soil aggregates and pores is affected with more intensity by site preparation practices and plant growth, and this way assessing soil structural quality in cultivated areas has become a common research topic, employing multiple techniques with different requirements of time, effort and technology.

Rapid, semi-quantitative data can be obtained in the field by direct evaluation of soil morphology, such as visual assessment of soil profile in pits (Tavares Filho et al., 1999; Boizard et al., 2013; Ball et al., 2007; Moncada et al., 2014). On the other hand, highly precise laboratory procedures have been developed to provide detailed information on soil structure. For instance, X-ray computed tomography (CT) is a powerful, non-destructive technique to visualize and quantify the soil structure properties in a tridimensional perspective at a micrometric scale (Garbout et al., 2013; Dal Ferro et al., 2013).

The validation of results obtained through in-field, expedite evaluations such as visual analysis, by means of sophisticated techniques such as CT scanning can potentially enhance our understanding of how soil structure is affected by soil tillage, and thus how sustainable a production system is (Garbout et al., 2013; Munkholm et al., 2013). However, despite of how simple or sophisticated a measurement technique is, any soil property to be used as a quality index has its interpretation limited to sampling conditions and spatial representativeness. Therefore, widespread use of soil structural quality indices is hindered by an incomplete perception of their spatial variability on the topsoil or throughout deeper layers, an issue that only recently has been studied through

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geostatistical approaches (Sander et al., 2008; Taina et al., 2013; Carducci et al., 2014b, 2015).

Many Oxisols reveal an inherently low bulk density (typically $<1.0\,g\,cm^{-3}$, sometimes $<0.7\,g\,cm^{-3}$) due to their granular structure, associated with a porosity pattern of large packing voids (Zinn et al., 2014). This feature leads to a high susceptibility to compaction when these soils are cultivated with conventional tillage and intensive agricultural management, even after the first heavy machinery traffic (Ajayi et al., 2009; Severiano et al., 2013).

In the Brazilian savanna biome (known as *Cerrado*), Oxisols developed under an ustic soil moisture regime have traditionally been cultivated for annual crops, although coffee (*Coffea arabica* L.) plantations have considerably increased their acreage in the last decades. Coffee plantations are perennial crops in which tillage and harrowing do not take place yearly unless for weeding purposes, but many times a year they require cultural practices chiefly conducted with tractor-led machinery. Thus, highly productive coffee plantations are among the most labor- and resource-intensive crops in tropical agriculture, and considerable efforts towards more sustainable production systems have been developed. One of the most promising of such production system combines the use of heavy gypsum dose (7–28 $Mg\,ha^{-1}$) with mechanical site preparation including subsoiling, and cultural practices such as planting grasses between rows.

This innovative system promotes strong improvements in chemical and physical properties, such as higher base saturation and water availability in soil deeper layers (Santos et al., 2014; Silva et al., 2015). In consequence, coffee bean productivity increases (Carducci et al., 2014b), and the overall environmental quality is enhanced (Serafim et al., 2011, 2013). However, there is limited information on how such favorable changes in soil structural quality would respond over time, which is critical since coffee stands have productive life cycles of two to three decades before being cut and replanted.

In this work, we aimed to assess if or how soil structure change, as assessment by visual analysis of the soil profile, can be validated by X-ray CT scan. An additional goal was to investigate using geostatistical techniques if these changes would vary spatially in the horizontal and vertical directions and over time. The hypothesis tested was that geostatistical analysis of X-ray CT scanning data can validate results from in-field visual analysis of soil profiles for detecting soil structural variability.

2. Material and methods

2.1. Study area

The study was conducted in two coffee plantations near São Roque de Minas, in the upper São Francisco river basin, Minas Gerais, Brazil. The soil studied is a very clayey Rhodic Haplustox (*Latossolo Vermelho* in the Brazilian System of Soil Classification—Embrapa, 2013), with ca. 86% clay, from which 55% is gibbsite and 25% is kaolinite, according to thermal analyses (Carducci et al., 2014a,b). We sampled two crops: a young (3 yrs-old, planted Nov. 2008) coffee stand at 20°15′45″S and 46°8′17″W, at an elevation of 850 m, and an older (6 yrs-old, planted Nov. 2005) stand at 20°11′35″S and 46°22′07″E, at an elevation of 841 m. Both stands are ca. two hectare in size and rectangular in shape, and although not contiguous, are located in the same soil. Both plantations were planted and conducted according to the soil conservation management system described below. The experimental design was completely randomized, in three replicates.

Coffee seedlings (Cv. *Catucaí*) were planted with a spacing of 0.65 × 2.50 m, along planting rows that approached contour lines, for soil conservation. In the planting rows, deep tillage was performed to a depth of 60 cm (50 cm wide), with a special implement consisting of a subsoiler coupled to a spade tool and a set of rotary hoes, and which has a fertilizer box attached for simultaneous application of chemical fertilizers. According to the manufacturer, this equipment aims to improve downward water flow where soil internal drainage is slow or impeded (Mafes, 2015). In this naturally acidic, nutrient-poor soil, fertility must be constructed by adding 4 $Mg\,ha^{-1}$ dolomitic limestone +1.9 $Mg\,ha^{-1}$ gypsum, to the whole area, and a NPK (8-44-0) fertilizer enriched with 1.5% Zn and 0.5% B), to a depth of 60 cm. Aiming to gradually increase base saturation in depth, a high dose of gypsum

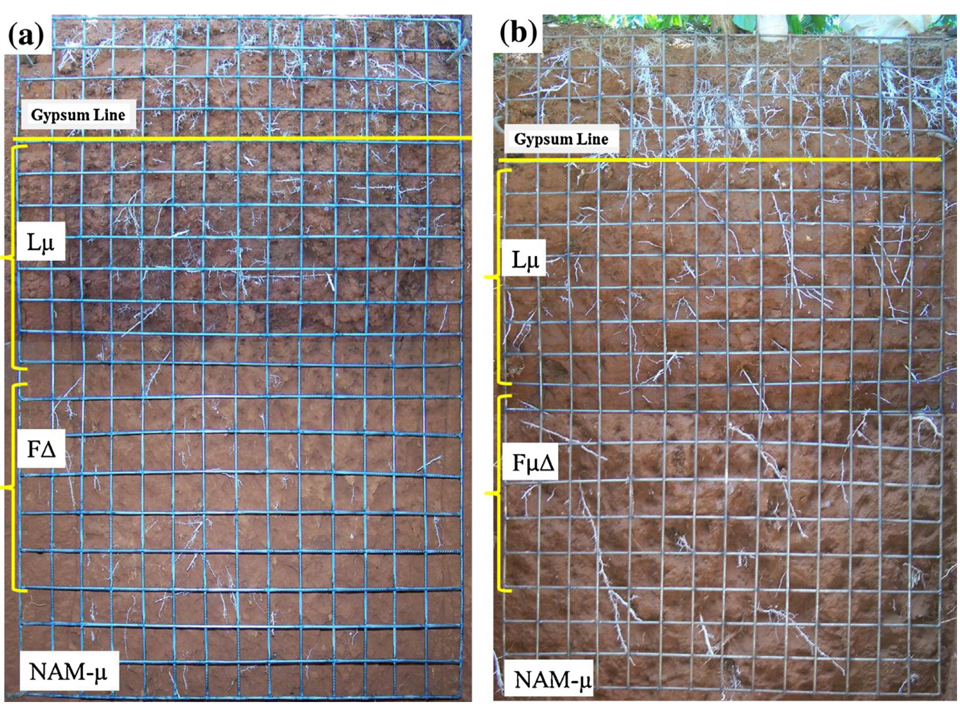

Fig. 1. Soil cultural profiles evaluated by visual analysis. (a) 3-yrs coffee stand, and (b) 6-yrs coffee stand.