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Quantifying physical and structural soil properties using X-ray microtomography

Chien Ling Tseng[a,*], Marlene Cristina Alves[b], Silvio Crestana[c]

[a] University of São Paulo (USP), São Carlos School of Engineering, 400 Avenida Trabalhador São-carlense, CEP: 13566-590 São Carlos, São Paulo, Brazil
[b] Paulista State University (UNESP), 56 Avenida Brasil, Centro, CEP: 15385-000 Ilha Solteira, São Paulo, Brazil
[c] Embrapa Instrumentation, 1452, Rua XV de Novembro, CEP: 13560-970 São Carlos, São Paulo, Brazil

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ABSTRACT

One of the current challenges in the study of recovering soil architecture is physically evaluating the internal soil structure in unconventional ways. The elaboration of consistent methods and physical parameters has become necessary for soil structural analysis. The aim of this study is to analyze the soil structures of two groups of recovering tropical soils and to simulate three-dimensional water movement pathways using unconventional methods and physical soil parameters. The following results were obtained from the analysis: 1) the S index was used as an indicator to effectively quantify the degree of management; 2) Qualisolo software was used to obtain the soil water retention curve (SWRC) of each management type; 3) the degree of anisotropy of the solid structure reflected the soil network; 4) the Euler-Poincaré number reflected the connectivity of the soil pores for each management type; 5) the Shannon entropy indicated the degree of randomness of the soil; and 6) the results of the Arya and Paris model and the simulations of water movement pathways are similar. In conclusion, the obtained results reflect the internal soil structures and their corresponding characteristics. Thus, the results can be used to predict the influence of soil architecture on the movement of water in the soil.

1. Introduction

The Brazilian cerrado (Savannah) biome is important for food and agricultural production due to its soil and climate. However, the cerrado soil has been intensively devastated by human activities over the past decade, and these activities have threatened sustainable resource use in the region. In this context, recovering degraded areas is important for ensuring sustainable soil use. However, determining how to evaluate the physical architecture of the recovering tropical soil and preserving its internal structure remains a challenge in evaluating this resource.

Among several minimally invasive and unconventional techniques and methods, X-ray computerized tomography (XCT) has become a common method for studying soil structure in recent decades. Petrovic et al. (1982), Hainsworth and Aylmore (1983) and Crestana et al. (1985) pioneered XCT methods for studies of soil density and measured the water content and water movement into the soil. Additionally, Appoloni and Cesareo (1994) performed microscanning and microtomography using an X-ray tube.

Although XCT has become popular in recent decades, applying it to tropical soils remains uncommon in the literature. Nevertheless, given the scarcity of related papers, some important tropical soil research using XCT should be highlighted. Vaz et al. (2011) evaluated two Brazilian Oxisols and established the scanning parameters for the soil. Passoni et al. (2014) characterized the soil macroporosity of a Rhodic Ferralsol using a second-generation X-ray microtomograph. In addition, Beraldo et al. (2014) used microtomography to quantify the porosity in areas with no tillage practices, conventional tillage practices and native forest. Recently, Marchini et al. (2015) applied CT to study recovering Brazilian Oxisols from the soil at 8.6 m deep, which has been exposed since the sixties, under different types of management strategies. Furthermore, Marchini et al. (2015) qualitatively evaluated recovering tropical soil under different management strategies using microtomography.

Thus, XCT could be used to develop indicators that can directly quantify soil internal structures using images, which would preserve the original soil. We selected 2 conventional and 5 unconventional physical parameters to characterize the differences in soil internal structures under different management types: bulk density, total porosity, soil water retention curve (SWRC), S index (Dexter, 2004), degree of anisotropy, Euler-Poincaré number and Shannon entropy. In addition, this study provides a two-dimensional visualization of the soil and

* Corresponding author.
E-mail addresses: chienlt86@86sc.usp.br (C.L. Tseng), mcalves@agr.feis.unesp.br (M.C. Alves), silvio.crestana@embrapa.br (S. Crestana).

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associated parameters and simulates water movement pathways in three dimensions. This approach can be used to visualize the recovery of soil structure under different management strategies at the pore level and to predict the behavior of water in the soil under different management types.

The capacity of soil to retain water is manifested in the SWRC, which is typically determined using methods that involve a funnel with a porous plate, tension table or pressure plate apparatus in the laboratory. In the field, different combinations of methods are used, e.g., a tensiometer is connected with a mercury manometer to determinate the water potential (Ψ), while time-domain reflectometry (TDR) and gravimetry are used to determine the volumetric soil moisture (Manieri et al., 2007). Due to the difficulty of experimentally obtaining SWRC, it is necessary to develop an indirect method to estimate SWRC, such as pedotransfer functions (PTFs) (Tomasella et al., 2000) and the Arya and Paris model, which was validated by Vaz et al. (2005) using 104 samples from the main soil class in Brazil.

The S index (soil physical quality) is obtained from the slope at the inflection point of the SWRC, which represents the relationship between the water content and the soil water potential, and is treated as a structural slope based on the pore distribution. Several important physical soil properties can be directly estimated using the S index (Dexter, 2004). For example, Varandas (2011) showed that the S index provides a quantitative measure to describe the soil degradation status with other parameters. However, there is controversy in the literature about applying the S index as a soil physical quality. For instance, van Lier (2014) stated that the S index assumes a unimodal distribution of pore radii, so it does not have additional value over the bulk density and is not capable of predicting the soil physical quality alone. Zeviani (2013) mathematically detailed the bimodal pore distribution using the SWRC, and Carducci et al. (2013) associated the S index with the adopted management system, i.e., as a structural quality indicator. Therefore, in addition to the S index, we consider all of the soil structural quality indicators, according to Moncada et al. (2015).

In this study, we used Qualisolo software (Naime et al., 2001), which applies the van Genuchten (1980) equation that was adjusted by the Arya and Paris (1981) model to obtain the SWRC and S index. In addition, this software was satisfactorily validated, which allows for analyzing a large quantity of samples in a short time that is impractical when using conventional methods (Vaz et al., 2005). In addition, the SWRC provided the permanent wilting point (θ_{pmp}), field capacity (θ_{cc}) and available water capacity (AWC) for each management system.

The degree of anisotropy strongly reflects the orientation of the elements inside a determined volume (Odgaard, 1997); thus, it influences the flux characteristics in a porous medium (Hernández Zubeldia et al., 2015). Bottinelli et al. (2016) demonstrated the stability of the degree of anisotropy in the formation of macropores during shrinkage in rice-cultivated soils.

The Euler-Poincaré number is a fundamental parameter that describes the connectivity of spatial structures (Vogel, 1997; Vogel and Roth, 2001). Recently, Martínez et al. (2015) used this parameter to study the geometry of aggregated soil; they concluded that this metric is capable of clearly reflecting the pattern of aggregates associated with different management types. Additionally, Katuwal et al. (2015) used a case study to show that this parameter is inadequate when isolated connections are predominant.

The next physical parameter is Shannon (2001) entropy, although this parameter is seldom included in soil analyses. Nevertheless, Gaur and Mohanty (2013) showed that Shannon entropy can be applied to understand the dominant physical control of spatiotemporal variability in soil moisture.

Applying the percolation theory in porous media involves the inclusion of random properties (Berkowitz and Ewing, 1998). For example, a study on the fingering phenomenon used a modified invasion percolation model (Onody et al., 1995). This study used an open source program published by Nakashima and Kamiya (2007) to simulate the transport properties inside the pores through three-dimensional microtomography, thus providing a visualization of water pathways in the soil under dry conditions. Such studies are important for evaluating management strategies and soil quality under various conditions.

The objective of this study is to apply unconventional methods and physical soil parameters to analyze the soil structures of two groups of recovering tropical soils and to predict the water movement pathways in three dimensions by using tomography.

2. Materials and methods

2.1. Experimental sites

The soil samples were obtained at Fazenda de Ensino e Pesquisa da Universidade Estadual Paulista “Júlio de Mesquita Filho” (Unesp) (Teaching and Research Farm of Paulista State University “Júlio de Mesquita Filho”) at the Ilha Solteira campus in the city of Selvíria (Mato Grosso do Sul State - Brazil). This area is located on the banks of the Paraná River (22° 22′ S and 51° 22′ W). Due to the construction of a hydroelectric power station at Ilha Solteira (São Paulo State) in 1969, subsoil containing the B horizon has remained exposed and has exhibited severe superficial compaction and a low presence of vegetation. The soil in the experimental area is a dystrophic Red Latosol characterized by advanced stages of weathering (Embrapa Solos, 2013).

2.2. Management description

The experiment implemented in this study included six management strategies, which were divided into two groups according to their texture similarity. Group I includes 1) soil from the native forest (Brazilian Savannah); 2) recovered soil (soil that had green manure applied over seven years from 1992 to 1999 and was then cultivated with *Brachiaria decumbens*); 3) recovering soil with *Astronium fraxinifolium* (Gonçalo-alves) + *Brachiaria decumbens* + sewage sludge; and 4) degraded soil (remaining soil from the construction of the hydroelectric power plant). Group II includes 5) recovering pasture soil and 6) degraded pasture soil. All samples were collected from the superficial layer (0–10 cm).

2.3. Physical analysis

In this study, the sampling analysis was based on microtomography instead of a field sampling campaign. The sample for microtomograph was collected with an acrylic tube to minimize image artifact and was always extracted from the upper side of an undisturbed block.

2.3.1. X-ray microtomography and image reconstruction

The commercial, high-resolution X-ray microtomograph and NRCon software (NRCon User Manual, 2016) from Embrapa Instrumentation were used to acquire and reconstruct tomographic images, respectively. The spatial resolution of the images was 4.96 μm, and the reconstruction parameters were adjusted according to Vaz et al. (2011).

To perform the statistical calculations, 500 images of 1000×1000 pixels were appropriately treated for each management type. Initially, the images were binarized using the Otsu (1975) method, which minimizes the sum of variances between image classes and the background. Second, CT-Analyser (2013) software was used to calculate the Euler-Poincaré number and the degree of anisotropy as both parameters are three-dimensional and do not have units. In addition, the same images were used in three-dimensional simulations. Except for the Shannon entropy, only one representative image was selected for each management type using the ‘entropy’ package in R (Hausser et al., 2012), a free software environment for statistical computing and graphics. This software was employed in this study due to the considerable amount of information contained in each image.

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