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Depth distribution of soil organic carbon in an Oxisol under different land uses: Stratification indices and multifractal analysis

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ABSTRACT

Understanding the depth distributions of soil organic carbon (SOC) content in a soil profile has become increasingly important to examine land use effects on soil carbon sequestration and soil quality. We addressed the variability of SOC in deep soil profiles under different land uses using the multifractal approach. In addition, classical indices such as proportion of SOC stored at the upper soil horizon and stratification ratios (SR) were used to evaluate organic matter accumulation near to the soil surface. Six soil profiles belonging to a *Rhodic Hapludox* were sampled at two sites with different textures under three land uses: native forest (NF) and sugar cane managed as continuous cropping, during either 5 (SuCa 5) or 10 (SuCa 10) years. Sixty-five soil samples per profile were analyzed for SOC. Soil carbon storage at the surface horizons and stratification ratios were significantly higher ($P < 0.05$) under SuCa 10 than under SuCa 5 and NF. Vertical distributions of SOC exhibited various degrees of scaling heterogeneity, so that those under SuCa 10 clearly showed multifractal behavior, while those under SuCa 5 and NF behave as quasi monofractal. In all the SOC depth distributions, the amplitude of the Rényi and singularity spectra was higher for positive than for negative q moments. Multifractal parameters estimated for the most positive moments were negatively correlated to SR, while those for the most negative q moments were best correlated to the proportion of SOC stored at the soil surface. Our results suggest that single scale analysis may not be sufficient to fully characterize vertical variability of SOC content.

1. Introduction

Soil organic carbon (SOC) content in mineral soils generally decreases with depth, even though Podzols are an exception to this rule. The vertical distribution of SOC is driven by inputs of litter at the soil surface, which incorporate mostly at the first centimetres of the soil profile, and by the distribution of plant roots and soil organisms, which also concentrates at the uppermost soil layers. Thus, variability in the depth distribution of SOC has been found to mainly depend on litter inputs, vertical distribution of roots and to a lesser extent on climate and clay content (Lorenz and Lal, 2005; Maquere et al., 2008). In general, organic matter transformations are affected by a number of factors and processes (such as decomposition, immobilization, mineralization, denitrification, nutrient cycling, etc.), which are expected to be more active near the soil surface. This is consistent with declining SOM contents as a function of depth. Understanding how these factors affect the vertical distribution of SOC contents and stocks with depth is essential for assessing soil carbon sequestration, soil quality, and land use effects on soil organic matter pools.

Because changes in land management are generally expected to have a higher impact on the upper soil layers, many studies about SOC contents in mineral soils have been limited to the first 30 cm of the soil profile. For example, Franzluebbers (2010) and Melero et al. (2012) found that changing an agricultural system from conventional tillage to no-till management produced an increase in SOC, and most of the carbon gained was concentrated in the first 5 cm of the profile. However, subsurface layers have been demonstrated to store large quantities of SOC and, therefore, this pool can't be ignored when estimating SOC sequestration (Mishra et al., 2009; Hobley and Wilson, 2016). Carbon accumulation below the surface soil horizon is mainly due to the effect of deep rooting systems (Lorenz and Lal, 2005) and may be enhanced by processes such as bioturbation and transport of dissolved organic matter by infiltrating water (Rumpel and Kögel-Knabner, 2011). Indeed, downward migration of organic matter, together with Al and Fe occurs during podsolization.

Changes in SOC vertical distribution at the uppermost soil layers have been often assessed using stratification ratios (SR), defined by Franzluebbers (2002) as the quotient between the value of organic C at the soil surface layer and its value at a deeper soil layer. This parameter can be considered as an index of SOC accumulation, as it provides

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information about organic matter losses and gains with depth. The SR index has been found useful to describe changes in SOC induced by land use changes. Conservation tillage is characterized by a greater SR, compared to conventional tillage (Franzluebbers, 2002, 2010; Sá and Lal, 2009; Melero et al., 2012). Also SR decreases with conversion of natural vegetation to agricultural land (Franzluebbers, 2010).

Enrichment of the soil surface layers in SOC strongly impacts soil quality, and affects soil chemical, physical and biological parameters that determine plant growth and ecosystem services. For example, it is widely recognized that increasing SOC enhances aggregate stability, water infiltration, and erosion control and ameliorates soil nutrient status (Lado et al., 2004a, b). Therefore, SOC accumulation and SR have been proposed as indicators of soil quality under diverse tillage methods (Franzluebbers, 2002, 2010; Melero et al., 2012).

The most common mathematical descriptions of SOC decline with depth in a soil profile assume a non-linear decrease, which is modelled as an exponential function. Although this approach has been largely successful (Hilinski, 2001), the adequacy of fitting an exponential model, however, may be not always valid (Maquere et al., 2008; Mishra et al., 2009). For example, Arrouays and Pelissier (1994) found an exponential decrease of SOC in forest soils with large amounts of organic matter. However, in cultivated soils, abrupt changes in SOC can occur at the boundary of the ploughed layer and the subsoil preventing the use of an exponential function for describing its depth dependence (Lorenz and Lal, 2005; Minasny et al., 2013). Discrepancies between experimental data and those estimated by an exponential model of SOC decrease have been mainly attributed to differences in the vertical distribution of roots and to land use and management effects (Lorenz and Lal, 2005).

Several other methods to explore the relationship between SOC and soil depth have been developed. Among them, spline functions, first proposed by Erh (1972), have been found to be useful to estimate continuous depth variations of SOC from discontinuous or categorical data, which are readily available for a number of soil profiles described, sampled and analyzed by morphogenetic horizons. Compared to discrete profiles, characterized by the average values in successive horizons, spline functions are viewed as a flexible tool for assessing continuous depth distributions of soil properties. The initial spline function method has been later refined, so that a modified function, called the *quadratic equal-area spline function*, was developed for reconstructing a continuous soil profile from the analysis of a small number of horizons (Ponce-Hernández et al., 1986; Bishop et al., 1999). More recently also non-parametric methods have been incorporated for modeling vertical distribution of soil properties, including SOC, such as peak functions (Myers et al., 2011) and bootstrapped Loess regression (Keith et al., 2015).

Spatial variability and heterogeneity are now considered as inherent to many soil properties and processes. Soil heterogeneity under native vegetation results mainly from soil formation factors. In cultivated soils additional heterogeneity can occur as a result of different land uses, and management practices. Therefore, intrinsic heterogeneity has been associated with natural variation in soils, whereas extrinsic variability has been rather related to variations imposed by crop production practices (Cambardella et al., 1994; Caridad-Cancela et al., 2005). Patterns of distribution of soil properties across horizontal and vertical scales have emerged as a fundamental topic in soil science, and methods for upscaling or downscaling soil information are increasingly demanded. As soil is a continuum, its properties are expected to be spatially auto-correlated at a certain scale (Burgess and Webster, 1980). Therefore, soil spatial variability, including SOC variability at different scales has been described quantitatively using geostatistics (Caridad-Cancela et al., 2005; Mishra et al., 2009). Geostatistical techniques have been also used together with depth distribution functions estimated by negative exponential functions (Mishra et al., 2009) or by equal area spline functions (Malone et al., 2009; Odgers et al., 2012) to predict and map SOC stocks. These studies concluded that both, spatial autocorrelation and depth distribution of SOC must be considered when estimating soil carbon sequestration.

Soil spatial variability exhibits a complex behavior, which results from both, irregularity and structure for different length scales (Burrough, 1983). Therefore, analysis of the scaling property of soil attributes by techniques, such as fractal and multifractal analysis (MFA), also has been found to be useful for characterizing the spatial heterogeneity of soil properties (Folorunso et al., 1994). Multifractal analysis (MFA) focusses on how a measure of mass varies with segment or box size (scale) and has been demonstrated to be an efficient method to characterize the spatial variability of soil properties (Caniego et al., 2005; Vidal-Vázquez et al., 2013). The MFA approach provides physical insight at various scales and doesn't require assumptions about stationarity or homogeneity of the studied data sets. While the semivariogram characterizes the scaling properties of the second moment, MFA provides information about higher moments and how these higher moments change with scale.

Recently also MFA has been used to describe the scaling heterogeneity of depth-dependent soil properties, including soil penetration resistance measured both, across profiles in the field (Siqueira et al., 2014; Wilson et al., 2016), and soil cores in the laboratory (Paz-Ferreiro et al., 2013), as well as soil porosity determined by X-ray computed tomography also in vertical soil columns (San José Martínez et al., 2010). However, scaling analysis of the depth dependent distribution of SOC using multifractals however has been not addressed until now.

Burning of sugarcane (*Saccharum officinarum*), either before or after harvest was a common practice worldwide, including Brazil, the leading country in sugarcane manufacturing. However, nowadays burning has been banned in several Brazilian states, including São Paulo State. Burning sugarcane residues obviously reduced the amount of surface organic matter available for incorporation into the soil, and therefore the end of burning generally results in increased SOC. Under continuously no-tilled sugarcane, however, several years may be required before changes in SOC content become evident. Also, potential rates of carbon sequestration under no-tilled sugarcane cropping systems have been only poorly quantified.

We hypothesized that single scale analysis may not be sufficient to fully characterize depth distributions of SOC. Therefore, the primary aim of this study was to explore the possibility and practicality of using multifractal formalism to evaluate the scaling patterns of SOC vertical profiles under the three land uses considered. Specifics objectives were: 1) to assess the effect of land use on the proportion of SOC stored at 0–30 cm and on the stratification ratio, 2) to evaluate if changes in land use and management modify the scaling property of SOC profiles, and 3) to investigate if there is a relationship between scale heterogeneity of SOC profiles and SOC stored at the uppermost layer or stratification ratio.

2. Material and methods

2.1. Study area, field sampling and laboratory analysis

The field work was conducted in the state of Sao Paulo, Brazil, at the morpho-structural unit named *Depressão Periférica* (Almeida, 1964), characterized by a smoothly undulated relief and altitudes varying between 570 m and 880 m. Parent materials are mafic rocks, and soils are mainly *Rhodic Hapludox* (Soil Survey Staff, 2014). Sugarcane is the main crop in the Center-South region of Brazil, the heart of the country's sugarcane industry. Almost 70% of the 1,800,000.000 ha cultivated with sugarcane in this region belong to the soil order *Oxisols.*

Two sites with different soil texture were selected. In each site three soil profiles were sampled, from which two were under sugarcane and the else one was in a neighboring plot under natural forest (NF). The cultivated plots represented two different land uses with continuous sugarcane in cycles of 5 and 10 years under no-tillage (SuCa 5 and SuCa 10, respectively). Table 1 gives the geographic coordinates