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Assessment of carbon storage under rainforests in Humic Hapludox along a climosequence extending from the Atlantic coast to the highlands of northeastern Brazil

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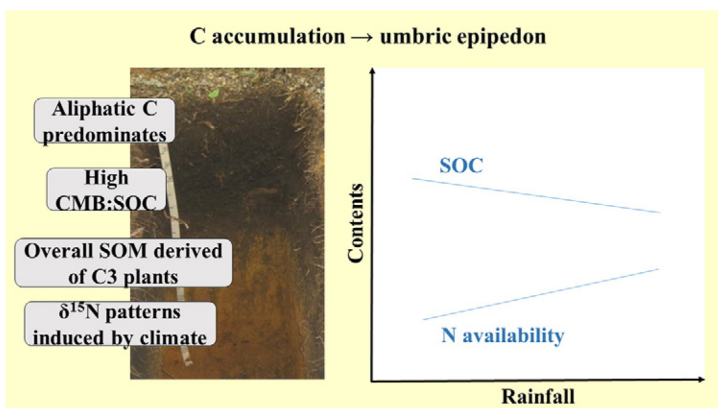
HIGHLIGHTS

- SOM was assessed in thick umbric epipedon in areas surrounded by semi-arid region.
- Soil carbon storage contrasts with the hot and humid tropical climate.
- The climate and recalcitrant SOM do not determine the umbric epipedon formation.
- ^{15}N patterns suggest that the low availability of N favors the accumulation of C.

GRAPHICAL ABSTRACT



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ABSTRACT

An understanding of the stock of soil organic carbon (SOC) in the umbric epipedon of Oxisols located in the tropical forests surrounded by a semi-arid region is limited but essential because of their importance in the global cycle of carbon (C). The purpose of this study was to assess the effects of climatic (temperature and rainfall), soil organic matter (SOM) composition and litter on the stability of C in surfaces and subsurfaces in five Humic Oxisols along a 475-km climosequence from 143 to 963 m a.s.l. in a tropical environment in northeastern Brazil. We assessed vertical changes in SOC; soil total nitrogen (N); C from the microbial biomass; $\delta^{13}C$, $\delta^{15}N$ and the humified composition of SOM; the composition of the humin (HUM) fraction by Fourier Transform Infrared (FTIR); and Thermogravimetry (TG) and Differential Scanning Calorimetry (DSC) at depth. The elemental and isotopic

Abbreviations: SOC, soil organic carbon; SOM, soil organic matter; HO, Humic Oxisols; CMB, C from the microbial biomass; HA, humic acids; FA, fulvic acids; HUM, humin; FTIR, Fourier Transform Infrared; DSC-TG, Differential Scanning Calorimetry and Thermogravimetry; TNS, total nitrogen in the soil; TCL, total C in the litter; TNL, total N in the litter; $\delta^{13}C_L$, $\delta^{13}C$ in the litter; $\delta^{15}N_L$, $\delta^{15}N$ in the litter; C:N_L, C:N ratio in the litter; 1Exo, first exothermic reaction; 2Exo, second exothermic reaction; Exo1%, percentage loss during the first exothermic reaction relative to the total loss of organic material; FLONA, Araripe-Apodi National Forest.

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composition of the litter samples were analyzed in all areas studied. The results indicated that the current climate and recalcitrant organic compounds are not preponderant factors in the formation of the umbric epipedon, as suggested by the partial influence of temperature and rainfall on SOM. In addition, SOM was dominated by easily decomposable compounds, as indicated by the predominance of aliphatic C–H groups in the HUM fraction in the FTIR spectra; by the thermal oxidation through DSC-TG, which revealed that approximately 50% of the HUM was composed easily decomposable compounds; and by the high proportion of organic C present in the microbial biomass. Values of $\delta^{13}C$ showed a predominance of C3 plant-C in SOM whereas $\delta^{15}N$ patterns indicated that N dynamics differ among the profiles and drive the accumulation of C. These findings can help to characterize the susceptibility of these soils to changes in climate and land use and the implications for the sequestration of soil C.

1. Introduction

Forest ecosystems account for more than 70% of terrestrial soil organic carbon (SOC) (Jandl et al., 2007), and the majority of SOC (approximately 60%) is present in the subsoil below a depth of 20 cm (Rumpel et al., 2002; Chabbi et al., 2009; Batjes, 2014). However, subsoil carbon (C) has drawn increasing attention in recent years (Fontaine et al., 2007; Sanaullah et al., 2011; Rumpel and Kögel-Knabner, 2011; Mora et al., 2014; Marín-Spiotta et al., 2014). Studies have shown that the stability of subsoil-C is related to the scarcity of fresh C in the subsurface (Fontaine et al., 2007), the physical protection of soil organic matter (SOM) in soil aggregates (von Lützow et al., 2006), the chemical composition influenced by pedological processes (Spielvogel et al., 2008; Mikutta et al., 2009), and labile and resistant C pools responding similarly to changes in soil temperature (Fang et al., 2005). Furthermore, the majority of these studies were conducted on soils containing low SOM concentrations at depth. The chemical composition and the factors regulating the stabilization of SOM in the umbric epipedon (>1.0 m) of Oxisols in tropical areas has rarely been studied.

The C stocks (0–30 cm) in the umbric epipedon of Brazilian Oxisols are in the order of 30.0 kg m^{-2} (Andrade et al., 2004). In contrast the adjacent soils in the Brazilian northeast (NE) semi-arid region are characterized by low C stocks (2.0–3.0 kg C m^{-2}), which indicates the critical influence of climatic on C accumulation influence (Bernoux et al., 2002). Thus, Humic Oxisols (HO), represent an important C sink and/or source and are a significant component of the global C (Poulter et al., 2014).

The occurrence of HO is common in southern and southeastern Brazil (humid tropical and subtropical environments); HO are associated with highland environments with mean temperatures below 18 °C (Lepsch and Buol, 1986; Brasil, 1972; Ker, 1997; Silva and Vidal-Torrado, 1999). The majority of HO studies are concentrated in these regions because the stability of SOM in these soils has, in part, been empirically linked to the mild climate. However, the identification of the effects of the current climate on the C stocks in these soils has been neglected. Contrary to expectations, in the NE region of Brazil in which the semi-arid climate prevails, these soils also have a thick umbric epipedon (>1.0 m), and this is not consistent with current climate conditions. These soils are under ecological tension (enclaves or ecotones) between the Dense Ombrophilous Forest and the Seasonal Semideciduous Forest and *Caatinga*, commonly located in the upper portion of a water basin/slope (Brasil, 1972). In this region, altitudes range from 150 m to 1200 m, with orographic rain that ensures precipitation above 1000 mm $year^{-1}$ (Araújo Filho et al., 2000; Velloso et al., 2002) and causes the emergence of tropical forests.

The variations in altitude show a variety of local climates that influence C stock (Garcia-Pausas et al., 2007). In addition, the climate determines plant communities, which can also influence SOM content and quality (Vinton and Burke, 1997). A recent theoretical model suggests that the limitation of nitrogen (N) to plants and to decomposing microorganisms, mediated by mycorrhizal fungi, would lead to an increase in soil C stock (Lindahl et al., 2010; Averill et al., 2014). There is also evidence that C from the roots, which could be more chemically recalcitrant because of the higher lignin content, significantly contributes to subsoil-SOM (Jobbágy and Jackson, 2000; Lorenz and Lal, 2005). In general, the chemical recalcitrance of subsoil-C has been supported because of the increase in the mean residence time of ^{14}C in subsurfaces (Paul et al., 1997).

C stability in HO remains partially understood and has been related to cold climates, acidity, high Al saturation and the association between C and the mineral fraction of the soil, particularly poorly crystallized forms of Al (Queiroz Neto and Castro, 1974; Lepsch and Buol, 1986; Ker, 1997; Marques et al., 2011) and crystalline Fe (Fontes et al., 1992) in addition to the redistribution of carbonized material (charcoal) in the soil over time by biological activity (Silva and Vidal-Torrado, 1999). These materials would be paleosoils formed during the Holocene under conditions favorable to the accumulation of SOM in the subsurface (Lepsch and Buol, 1986).

We hypothesize that C accumulation in the umbric epipedon increases with an increase in altitude because microbial activity is inhibited at low temperatures (Garcia-Pausas et al., 2007). We also hypothesize that the stability of the C in this horizon is due to the complex chemical nature of the SOM. The purpose of this study was to assess the effects of climate (temperature and rainfall) on the accumulation and composition of SOM and litter in the surface and subsurface HO soils using isotopic, spectroscopic and thermal degradation techniques.

2. Materials and methods

2.1. Study areas

The selection of study areas was based on the occurrence of HO in NE Brazil, as indicated in previous pedologic studies (Brazil, 1972; 1973; Araújo Filho et al., 2000; Marques et al., 2011; Embrapa, 2012) and the knowledge of the pedologists of the region. The study was conducted along a 475-km climosequence to encompass the bioclimatic variation of occurrence of HO in the NE region of Brazil, extending from the sedimentary coastline toward the inland semi-arid region in NE Brazil and at altitude ranging from 143 to 963 m a.s.l (Fig. 1). The locations of soil profiles, soil classification, altitude, rainfall, air temperature, parent material and vegetation in the studied areas are shown in Table 1.

2.2. Sampling and processing soil and litter

The five study site were selected using the map of soils in Brazil (Embrapa, 2012). One pit was dug at each site, after soil sampling with an auger to identify a representative soil of the area, and studied according to the Brazilian protocol of soil science (Embrapa, 2013) and each profile was located on top of a slope under natural vegetation (Table 1). Soil samples were collected from profiles at depth intervals from 10 cm to 100 cm for SOC analysis, total soil N (TNS), $\delta^{13}C$ and $\delta^{15}N$. An identical sampling procedure was repeated to collect samples for analysis of microbial biomass C (CMB). In the field, soil samples were immediately cooled and then kept at 4 °C until they were analyzed. Additional soil samples was taken for morphological description of profiles (data not shown) according to Embrapa (2013) to identify the umbric epipedon, which was subsequently verified by chemical