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Effect of no-tillage and amendments on carbon lability in tropical soils

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ABSTRACT

The effects of organic matter on soil properties depend on its content and quality. Understanding the carbon dynamics and soil organic matter (SOM) quality is crucial for evaluating the sustainability of agricultural systems, the global carbon cycle, elemental weathering, and soil capacity to withstand physical damage. The objective of this study was to assess SOM quality in four Brazilian locations, two of them under no-till (NT) conditions in which soils were amended with lime and gypsum, and the other two soils amended with sewage sludge or compost under conventional system. Soil samples were collected at a depth of 0–0.1 m in four long-term field experiments: (i) a NT system with limestone amendment and re-amendment; (ii) a NT system with gypsum amendment and re-amendment; (iii) a soil amended with sewage sludge for 13 consecutive years; and (iv) a soil amended with just one sewage sludge and composted sludge. Physical and chemical fractionation of SOM and analyzed samples were performed by laser-induced fluorescence (LIF; soil) and nuclear magnetic resonance (NMR; HS). In addition, the Carbon Management Index (CMI) was calculated to evaluate the impacts of soil management practices on organic matter quality. The highest carbon content was found in the free light organic fraction in all experiments, followed by the silt + clay fraction. NMR detected predominance of the C-alkyl and C—O-alkyl organic radicals. Both fluorescence and LIF techniques generated Humification Indexes with similar trend. There were differences between the experimental sites when SOM granulometric fractions were analyzed, but no differences in the predominant organic compounds were observed. Soil quality, assessed by CMI, was generally improved with limestone, gypsum, compost and sludge.

1. Introduction

Soil organic matter (SOM) affects physical, chemical, and biological properties of soils and represents the primary pool of carbon (C) and plant nutrients (Kinchesh et al., 1995). The effects of organic matter on soil properties are dependent on its content and its quality, and change according to climatic conditions, nature of the parent material, and soil type (Stevenson, 1994). Knowledge of the carbon dynamics and SOM quality is crucial for understanding the sustainability of agricultural systems, the global carbon cycle, elemental weathering, and soil capacity to withstand physical damage (Kinchesh et al., 1995).

The dynamic processes involved in the transformation of SOM are highly sensitive to environmental conditions (Guerra et al., 2008). The primary variables that determine the persistence of C in soils are temperature and annual rainfall. In the humid tropics, higher temperatures and higher precipitation regimes lead to higher rates of decomposition of organic matter in soils than in temperate regions (Bayer and Mielniczuk, 2008; Resck et al., 2008). In wet subtropical regions, organic matter is estimated to decompose at an annual rate of 3.2%, approximately three times faster than in the temperate zone (1.0%).

Under an agricultural perspective, no-till (NT) management systems improve the quality of tropical and subtropical soils. Balesdent et al. (2000) highlight the increase of organic matter stocks and the improvement of soil aggregate stability, although the magnitude of these effects depends on soil type and climatic conditions. Established in Brazil in the 1970s, no-till management has since improved agricultural sustainability in areas at risk for soil erosion and nutrient loss and has permitted agricultural expansion to new areas, especially those previously dominated by native grasslands.

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Many amendments are applied in tropical soils by farmers in order to improve the soil quality. Among the amendments, limestone neutralizes the adverse effects of soil acidity on plants and improves crop productivity. On the other hand, gypsum has been used to decrease aluminum toxicity and to improve Ca, Mg and S contents in tropical soils (Caires et al., 2011). Other amendment frequently used by growers is the composted sewage sludge (or biosolid). Its disposal in landfills is a promising alternative, especially in densely populated areas that produce large volumes of sludge (Silveira et al., 2003). Monitoring SOM quality and the humic and fulvic fractions of sludge is crucial for ensuring that the use of sludge in soils is environmentally safe and agriculturally efficient (Bertoncini et al., 2005).

A good understanding of the structural changes that SOM undergoes during the humification process is a priority for humid tropical soils. The nature of humus and the distribution of humified fractions vary with climate, plant cover, soil acidity, the presence or absence of cationic nutrients, drainage, and soil texture (Zech et al., 1997). All these soil attributes and soil processes influence the array of decarboxylation, dehydration, oxidation, and hydrolysis reactions, thus influencing the humification process.

Advances in analytical techniques, especially in spectroscopic methods, allow a detailed description of SOM structure. The technique of ^{13}C cross-polarization magic-angle spinning nuclear magnetic resonance (^{13}C CP-MAS NMR) has been widely applied in studies of humic substances (HS) and has led to important advances in knowledge about the structural composition of humic and fulvic acids (Knicker et al., 2006). Additionally to ^{13}C NMR data, analyses by Fourier Transform Infrared spectroscopy (FTIR) have helped the identification of functional groups such as carboxyls, hydroxyls, polysaccharides, amines, and others (Stevenson, 1994). FTIR studies have used cluster analysis to identify and distinguish between groups of compounds (Pappas et al., 2008). Several researchers have used indices based on UV–vis spectroscopy to quantify the degree of humification of humic substances extracted from organic matter of diverse origins (Plaza et al., 2007). Another technique for studying HS is fluorescence, which provides an estimation of the humification degree (Milori et al., 2002), thereby providing insights into the chemical reactivity and structure of SOM.

Using SOM characterization techniques mentioned before, it is possible to calculate the Carbon Management Index (CMI) for evaluating the effect of management practices commonly adopted in tropical soils, such as sewage sludge inputs (tillage systems) and application of limestone and gypsum under no-tillage systems. The CMI, originally proposed by Blair et al. (1995) can be used to assess soil quality based on information related to soil organic C dynamics. This index is a measure of the relative sustainability of different systems and can be used to compare the changes that occur in the contents of total C and labile C as a result of agricultural management practices (Vieira et al., 2007).

In this study we assessed SOM quality in four Brazilian locations, two of them under no-till (NT) conditions and two under conventional systems. The two soils studied were amended with lime and gypsum, and the other two soils with sewage sludge or compost under conventional systems. The experimental areas not cultivated under NT were amended either with a single application of sewage sludge (sludge or sludge compost) or with sewage sludge for 13 consecutive years (sludge only).

2. Materials and methods

2.1. Sample collection and experimental design

Compound soil samples composed of 20 subsamples were collected at a depth of 0–0.1 m from four experimental sites. Samples were air-dried and sieved through a 2-mm mesh. The four study sites were:

a) An experiment installed in a Rhodic Hapludox (Soil Survey Staff, 2010) in Ponta Grossa, state of Paraná (PR), Brazil (25°14′09″S, 50°00′17″W), managed under a no-till system for more than 15 years. A randomized complete block design was used in a split-plot arrangement with three replications. The main plots (8.0 m × 6.3 m) consisted of superficial liming at the rates of 0, 2, 4, and 6 Mg ha^{-1}, calculated to raise the base saturation of the topsoil (0–20 cm) to 50, 70, and 90%, respectively. The dolomitic lime used contained 176 g kg^{-1} Ca, 136 g kg^{-1} Mg, and 84% effective calcium carbonate equivalent (ECCE), and was broadcasted on the soil surface in July 1993. Between November 1993 and May 2000, the following crops were farmed in rotation: soybean (*Glycine max*) (1993–1994), vetch + black oats (*Vicia sativa* + *Avena strigosa*) (winter 1994), maize (*Zea mays*) (1994–1995), soybean (1995–1996), wheat (*Triticum* spp.) (winter 1996), soybean (1996–1997), triticale (*Triticum* + *Secale*– plant breeder crossed wheat with rye) (winter 1997), soybean (1997–1998), black oats (winter 1998), soybean (1998–1999), black oats (winter 1999), and soybean (1999–2000). In June 2000, the main plots were divided in two subplots (4.0 m × 6.3 m) for the study of surface re-liming influence (196 g kg^{-1} Ca, 130 g kg^{-1} Mg, and 90% ECCE) at the rates of 0 and 3 Mg ha^{-1}. The reapplied rate was calculated to raise the base saturation in the topsoil (0–20 cm) to 65% (Caires et al., 2000) of the treatment 4 Mg ha^{-1} of lime made in July 1993 (pH 0.01 M $CaCl_2$ of 4.6; total CEC – pH 7.0 of 110.8 mmol$_c$ dm^{-3}; and 41% of base saturation). After this second limestone application, the following crops were cultivated: black oats (winter 2000), maize (2000–2001), black oats (winter 2001), soybean (2001–2002), black oats (winter 2002), soybean (2002–2003), wheat (winter 2003), soybean (2003–2004), black oats (winter 2004), maize (2004–2005), black oats (winter 2005), soybean (2005–2006), black oats (winter 2006), soybean (2006–2007), black oats (winter 2007), soybean (2007–2008), black oats (winter 2008), maize (2008–2009), wheat (winter 2009), and soybean (2009–2010). The soil contained: pH_{CaCl_2} = 4.0; organic carbon = 20.6 g kg^{-1}; $P_{Mehlich}$ = 18.6 mg kg^{-1}; $K_{Mehlich}$ = 2.1; Ca_{KCl} = 15.8 e Mg_{KCl} = 6.1 mmol$_c$ kg^{-1}. The soil granulometric composition was: clay = 295; silt = 240 and sand = 465 g kg^{-1}. More details about the experimental area and the effects of amelioration of topsoil and subsoil acidity by surface liming and re-liming on the soybean and wheat performance can be found in Caires et al. (2006, 2008).

b) An experiment carried out on a Rhodic Hapludox Hapludox (Soil Survey Staff, 2010) in state of Ponta Grossa (PR), Brazil (25°14′09″S, 50°00′17″W) had previously been used as pastureland. A randomized complete block design was used in a split-plot arrangement with three replications. Plot size was 8 m × 7 m and subplot size was 4 m × 7 m. The treatments consisted of 6 Mg ha^{-1} of gypsum applied on the soil surface in September 2004 to subplots within plots where gypsum had been surface-applied at 3, 6, and 9 Mg ha^{-1} in October 1998. Between November 1998 and May 2004, the following crops were planted in rotation: soybean (1998–1999), barley (*Hordeum vulgare* L.) (winter 1999), soybean (1999–2000), wheat (winter 2000), soybean (2000–2001), maize (2001–2002), and soybean (2002–2003 and 2003–2004). Following the second application of gypsum, the following crops were cultivated: maize (2004–2005), soybean (2005–2006 and 2006–2007), maize (2007–2008), soybean (2008–2009), black oats (winter 2009), and soybean (2009–2010). The agricultural gypsum used in the experiment contained 235 g kg^{-1} Ca,