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Can highly weathered soils under conservation agriculture be C saturated?

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ABSTRACT

Soil organic carbon (SOC) plays an essential function in global agroecosystems. Conservation agriculture (CA) associated with diverse and high C-input is an important tool to increase SOC, improve soil quality, and increase agronomic productivity. However, the information about the potential of highly weathered soils under CA to accumulate SOC, and when the SOC saturation may occur, is scarce. This study was based on the hypothesis that in highly weathered soil from tropical and subtropical agro-ecosystems, the potential to store SOC lies more in the sub-soil than in surface layers and is determined by nutrient scarcity. Thus, the aim of this study, performed in a long-term incubation experiment (30 months), was to: (i) assess the SOC flow and mineralization based on CO_2-C emissions for estimating SOC accumulation; (ii) evaluate the impact of nutrient scarcity on C accumulation efficiency by soil layers; and (iii) determine when C saturation occurs in these soils. The incubation study was performed in three Brazilian Oxisols under long-term CA, and was comprised of four amounts of C-inputs (0, 6, 12 and 24 Mg C ha^{-1}) added at 0, 10 and 20-months to three soil layers (0–20, 20–40 and 40–100 cm). The CO_2-C emission was 19.0, 9.0 and 7.0% higher in the 0–20 cm than that in 40–100 cm layer for Ponta Grossa, Londrina and Lucas do Rio Verde sites, respectively, which was associated with higher antecedent SOC content and fertility status. A higher SOC accumulation efficiency was observed for the 0–20 cm layer than in deeper layers. Nutrient scarcity in deep soil layers; especially that of P, Ca^{2+} and Mg^{2+}; was the driving force limiting SOC accumulation. Carbon saturation was not achieved indicating a high SOC storage capacity in these soils. Because these and similar soils cover a large global area, they possess a large C sink to mitigate atmospheric CO_2-C. The potential SOC storage estimated for 20–100 cm layer based on this study and upscaling for 1/3 Brazilian Oxisols (100 million ha) may offset 0.06 to 0.36 Pg C yr^{-1} or 5.5% to 32.7% of the global annual greenhouse gas emissions by land use change.

1. Introduction

Soil organic carbon (SOC) plays an essential role in the terrestrial biogeochemical cycles, and soils may be a source or sink of atmospheric CO_2 depending on land use and management (Lal, 2004). Global estimates of historical C losses by land use (LU) and land use change (LUC) for the period 1870 to 2014 (Houghton, 2014; Le Quéré et al., 2014) range from 108 to 188 Pg C (mean = 148 Pg C; 1 Pg = 1 billion ton). Loss of C by cultivation from the world soils is estimated at 78 Pg C (Lal, 2004) representing 5.0% of the total SOC stored presently in the world soils (to 1-m depth). Greenhouse gas (GHG) emissions with strong impacts on atmospheric composition (Houghton, 2014; Le Quéré et al., 2014) include deforestation and burning of native vegetation (67 Pg C) and represent 10.8% of the C stock in terrestrial vegetation (620 Pg C). The annual emissions from fossil fuels and cement production (10.1 Pg C) plus LU and LUC (1.1 Pg C) to the atmosphere are11.2 Pg C (Houghton, 2014; Le Quéré et al., 2014).

Conversion of natural vegetation into agricultural land using conventional tillage (CT), and the maintenance of continuous plowing which aggravates aggregate disruption and low soil organic matter (SOM) protection, leads to SOC depletion (Bruun et al., 2015; Cambardella and Elliott, 1993; Churchman et al., 2010; Puget and Lal, 2005; Sá et al., 2015). In contrast, conservation agriculture (CA)

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associated with high and diverse C-input may restore soil aggregation and accumulate SOC over time (Bayer et al., 2006; Dick, 1983; Ogle et al., 2012; Sá et al., 2001; Sá et al., 2015; Tivet et al., 2013). However, scientific data about how much C can be accumulated in highly weathered soils in response to management are scarce.

Numerous studies have demonstrated a linear relationship between SOC accumulation and C-input (Kong et al., 2005; Kundu et al., 2007; Larson et al., 1972; Sá et al., 2015; Sun et al., 2013) indicating that C saturation takes a long time, and varies with the environment and management factors. Further, SOC accumulation occurs mostly in the surface 0–20 cm layer (Kuhn et al., 2016; Powlson et al., 2016). However, some reports on tropical soils indicate C sequestration potential in the sub-soil (Boddey et al., 2010; Jantalia et al., 2007; Sá et al., 2015) and that the overall C sink capacity depends more on soil type (clay content and mineralogy) than climate (Mathieu et al., 2015). Yet, some studies have also indicated a little or no SOC accumulation even after a long-term C-inputs, especially in the surface layers (Campbell et al., 1991; Chung et al., 2010; Gulde et al., 2008). This lack of relationship between SOC accumulation and C-inputs indicates a finite SOC sink capacity and of the SOC saturation level (Six et al., 2002).

Most studies regarding the effect of SOC saturation on SOC accumulation have been conducted in soils of temperate climate with high C contents (Chung et al., 2010; Feng et al., 2014; Gulde et al., 2008; Poirier et al., 2013; Stewart et al., 2012; Stewart et al., 2008). However, the current knowledge regarding C saturation in highly weathered soils and for a range of soil depths are scarce (Reis et al., 2014; Santos et al., 2011). Therefore, some important questions which needs to be addressed include: 1) what is the potential magnitude of these soils to accumulate C?, 2) what are the constraints that limit C accumulation?, and 3) how long does it take to attain soil C saturation?

Highly weathered soils (e.g. Oxisols) occupy ~7.5% of the global ice-free land area, 23% of land surface of the tropics (Michéli et al., 2006), and about 300 million ha (Mha) in Brazil (Embrapa, 2006). This large land area comprises a vast potential of global SOC sequestration. Highly weathered soils vary widely in chemical and mineralogical characteristics from those of temperate soils (Sposito, 2008), with different pathways in SOC stabilization. These soils are characterized by low-activity 1:1 clay minerals (e.g., kaolinite), high Fe and Al oxides content (e.g., gibbsite, hematite and goethite), and pH dependent sequestration (Schaefer et al., 2008). Furthermore, Oxisols of Brazilian agro-ecosystems are characterized by low natural soil fertility, low available phosphorus (P) and high concentrations of exchangeable Al^{3+}, especially in deep soil layers (Sá et al., 2009). Because of the low inherent nutrient reserves, processes moderated by microbial biomass C (MBC) can be severely constrained (Cleveland et al., 2002).

Several laboratory incubation studies, conducted since 2000s, have strengthened the scientific knowledge relating SOC saturation to its stabilization (Kimetu et al., 2009; Poirier et al., 2013; Stewart et al., 2008). These studies indicate the impact of C-input in soils of different C contents on SOC sequestration (Stewart et al., 2008). Furthermore, the laboratory incubation studies can be managed to create an optimal environment for C cycling (Curtin et al., 2012; Jastrow et al., 2007) by controlling factors that affect growth of microbial biomass (i.e., temperature and soil moisture regime). Long-term laboratory experiments are also important to assessing simultaneously the CO_2-C fluxes and SOC dynamics based on different amounts of C-inputs (Kuzyakov, 2011).

The rational of conducting this study lies on the fact that the disruption and fragmentation of macroaggregates by plowing exposes organic compounds hitherto protected against microbial attack and aggravating emission of CO_2 to the atmosphere while exacerbating SOC depletion (Elliott, 1986; Jastrow, 1996; Six et al., 2000; Tivet et al., 2013). Further, the time required to restore the SOC level depends on the adoption of best management practices (BMPs) associated with the amount, diversity and frequency of C-input. However, highly weathered soils have some specific mineralogical characteristics and fertility attributes leading to differences in SOC stabilization compared with those of less weathered soils of temperate regions.

The present study was based on the hypotheses that the large potential to store SOC in highly weathered soils resides more in C-poor subsoil than in surface layers and the C sink capacity is limited by the scarcity of plant nutrients. These hypotheses were tested on soil samples obtained for 0–20, 20–40 and 40–100 cm depths were obtained from contrasting long-term CA experiments (see Fig. 1). Soils from these experiments and depths have a contrasting range of SOC contents and fertility status, thus facilitating the assessment of the impact of nutrients scarcity and SOC saturation deficit on SOC accumulation and saturation. Furthermore, the data from long-term incubation studies using highly weathered soils are scarce but important to identify strategies to manage SOC sequestration efficiency, and to mitigate anthropogenic effects on climate change. Thus, this study aims to understand why and how the accumulation of C in sub-soil of Oxisols is not only governed by biomass-C input (amount, quality and frequency) but also by low nutrient availability of P and bases (Ca^{+2} and Mg^{+2}) and high concentration of exchangeable aluminum (Fig. 1). The specific objectives of this study were to: (i) evaluate CO_2-C emissions from surface vs. subsoil layers, based on amount of C-inputs added in a long-term CA soil, (ii) assess the impact of nutrient scarcity on C accumulation efficiency in different soil layers; and (iii) determine the time when C saturation can occur in these highly weathered Oxisols of subtropical and tropical agro-ecosystems.

2. Materials and methods

2.1. Long-term conservation agriculture experimental sites location and description

Three long-term tillage experiments were selected representing diverse climate environments and contrasting agro-ecosystems in Brazil (Table 1). These sites included: (i) the experimental station of Agronomic Institute of Paraná (IAPAR) located at Ponta Grossa city (25°09′S, 50°09′W), representing a subtropical area in southern Brazil, and hereafter designated as PG site; (ii) the experimental station of EMBRAPA-Soybean in Londrina city (23°11′S, 51°11′W) characterized by a transition environment between subtropical to tropical climate, and hereafter designated as the LDN site, and (iii) the experimental station of Rio Verde Foundation at Lucas do Rio Verde city (13°00′S, 55°58′W) representing a typical tropical climate located within the Cerrado biome, central-western Brazil, and hereafter designated as the LRV site. Additional descriptions and details about the experiments are presented in Barreto et al. (2009) and Sá et al. (2015).

At the PG site, the native vegetation prior to the conversion into agricultural land use consisted of subtropical "prairies" dominated by C_4 grass species and occurrence of subtropical gallery forests. The conversion of the native vegetation to agricultural land use was done in 1967, and was maintained under pasture for 10 years. In 1978, part of this area was converted to annual crops, cultivated to soybean for 3 years with conventional tillage (CT) until the establishment of the CA experiment in 1981. At the LDN site, the native vegetation prior to the experiment consisted of a secondary sub-montane, semideciduous forest. In 1967, this area was converted to agriculture and was cultivated to soybean with CT for 10 years. After that, the soil was managed by CA for 12 years until the beginning of the CA experiment in 1989. At the LRV site, the native vegetation prior to the experiment was the Cerrado forest characterized by tree species of 8 to 20 m height (Sclerophillous and Xeromorphic). The native vegetation was converted to agricultural land use in 1986, cultivated with CT until 2001 and converted to CA experiment thereafter.

2.2. Soil samples and incubation experiment procedure

Soil samples for incubation were obtained, in 2009 for the PG and LRV sites and in 2012 from the LDN site, from 0 to 20, 20–40 and 40–