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Soil carbon stocks of Ultisols under different land use in the Atlantic rainforest zone of Brazil

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A B S T R A C T

Reforestation has a great potential on soil carbon sequestration resulting from continuous deposition of plant residues above- and belowground. The purpose of this study was to answer the following questions: (1) did reforestation with 35 years old rubber tree plantation and 3 and 5 years old eucalyptus plantations enhance SOC accumulation up to 1 m depth? (2) How much did the conversion of forest into pasture changed the origin of SOC accumulated up to 1 m depth? (3) How much did the conversion of pasture into eucalyptus plantation changed the origin of SOC accumulated up to 1 m depth? The experimental area in this study was: 3-year-old eucalyptus plantation; 5-year-old eucalyptus plantation; 35-year-old rubber tree plantation and 50-year-old unfertilized pasture. SOC was determined by dry combustion in six layers (0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm). The natural abundance of ^{13}C technique was used to determine the relative contributions of C_3 and C_4 plants derived C to the total SOC accumulated up to 100 cm. Rubber tree showed significantly higher SOC stock (219 Mg ha^{-1}) at a depth of 0–100 cm. Pasture (176 Mg C ha^{-1}) and 3 (148 Mg C ha^{-1}) and 5 years old (160 Mg C ha^{-1}) eucalyptus plantations had smaller C stocks and were similar to secondary forest (168 Mg C ha^{-1}) and there was a narrow variation of SOC storage over the soil profile. The differences in $\delta^{13}C$ values were more pronounced in the upper soil layers and below 40 cm these differences progressively decreased until a very small $\delta^{13}C$ variation up to 100 cm. Rubber tree plantation, compared to secondary forest, enhanced around 46 Mg ha^{-1} the SOC stored up to 1 m depth and 2 year old gap between the two eucalyptus plantations was enough to enhance the SOC accumulation in 14 Mg ha^{-1}. The accumulation of SOC decreased slightly from 40 to 100 cm. 50 years after the conversion of forest into pasture allowed the incorporation around 33 Mg ha^{-1} of C_4-derived C up to 100 cm and around 14% of SOC accumulated in eucalyptus plantations was C_4-derived C up to 100 cm. The accumulation of SOC in all vegetable covers is still derived from the previous vegetation at a depth deeper than 60 cm.

1. Introduction

The Atlantic rainforest zone used in this study is historically one of the most affected by deforestation in the lowest areas of remaining forests. Besides, the inappropriate management of these remaining forests such as unsustainable timber production and harvesting, overharvesting of fuel wood and fires at the edge of forest, partially removed or caused damage to the forest components, not replacing or recovering them within a reasonable time frame (DeFries et al., 2007). A similar phenomenon happened in abandoned grassland areas affected by constant fires and weed species invasion (Müller et al., 2006). As a result, these lands became propitious areas for resprouting trees and weeds, with significant reduction of soil productivity capacity. Later on these lands became an animal grazing area, contributing to the soil depletion cycle. Given this reality, one initiative is forest plantations, which are expanding lately in the region. For the last 50 years approximately, there was an incentive in rubber tree plantation through the “Program for rubber tree plantation”, an experimental project that could increase employment and income in poor areas of the Minas Gerais state, Brazil. However, with reduction in the rubber price, rubber tree plantations were abandoned over the years. Recently, as a new attempt to deploy rubber trees plantations, due to a more favorable rubber price, the project was recovered and new plantations were introduced in the region. In addition, eucalyptus was introduced through the “Planted Forest Project” in partnership with Technical Assistance and Rural Extension Enterprise of Minas Gerais State (Emater-MG) and State Secretariat of Agriculture, Livestock and Supply (Seapa).

Thus, after the deployment of these projects, the current landscape in the region, besides remaining forest and pasture, old rubber tree plantations, most of them abandoned and few with homogeneous stands and well developed; and young plantations of rubber tree and eucalyptus. To encourage more and more local farmers to join the

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reforestation practice, it is urgent to emphasize environmental services such as carbon sequestration in both aboveground and belowground (Lima et al., 2006; Shimamoto et al., 2014). Therefore, study of the potential of these forest plantations in storage soil organic carbon (SOC) up to 100 cm can be a positive strategy.

Tree plantations have a prominently feature among tools for carbon sequestration (Jackson et al., 2005): Primary plant production and soil microbial activity are the two main biological processes governing inputs and outputs of soil organic matter (SOM) (Montagnini and Nair, 2004). Trees through litter deposition, root biomass and turnover and root exudates are a high source of soil organic C (SOC) (Rasse et al., 2005). Forest plantations have been expected as a measure to regain SOC due to high incorporation of above and below-ground biomass, recalcitrant carbon inputs and deep rooting systems. For example, fine roots of shrubs and trees are a critical carbon source for deep SOC; tree roots production accounts for nearly 33% of the annual net primary production and extends more deeply than the roots of grasses and herbs (Lal, 2005; Don et al., 2010; Pérez-Cruzado et al., 2012).

Consequently, forest soil is a potential pool of C store and plays an important role in the global C cycle (Lal, 2005; Jandl et al., 2007). According to Yang et al. (2005) soil C sequestration potential in rubber tree plantations is significantly linearly correlated to the plantations age and ranges from 111 Mg C ha^{-1} to 202 Mg C ha^{-1} in Latosols in China at 100 cm depth. Maggiotto et al. (2014) in Brazil reported that the growth of the rubber tree from 4 to 15 years old resulted in an SOC sequestration rate of 1.1 Mg C ha^{-1} yr^{-1} to a 60 cm depth. Eucalyptus as well as rubber tree showed a high potential of accumulation of C in soil depth. Zinn et al. (2002) found an average of 50 Mg ha^{-1} at 60 cm depth of SOC stock in eucalyptus plantations. Gatto et al. (2010) showed SOC stock ranging approximately from 100 to 170 Mg ha^{-1} to a depth of 100 cm.

The conversion of degraded pasture into forest plantations or natural forest into pasture, directly affects the C input pathways. Forests are predominantly composed of plants possessing the C_3 photosynthetic pathway which has a ^{13}C abundance of approximately -35 to -20‰. On the other hand, C_4 photosynthetic pathway is typical of grass and usually shows ^{13}C abundance between -19 and -9‰. So, the natural ^{13}C abundance method can be used to determine the relative contributions of C_3 and C_4 plants derived C in the total SOC (Balesdent et al., 1987; Bernoux et al., 1998). While, Maggiotto et al. (2014) verified after 15 years of rubber tree growth, increased levels of C_3 derived C that ranged from 75 to 82% in the 0–60 cm depth. Lima et al. (2006) showed that after conversion from pasture to eucalyptus, less than 10% of SOC was derived from C_4-C by the third eucalyptus rotation, and almost all SOC was derived from C_3 species by the end of the fourth rotation.

In this context, the purpose of this study was to answer the following questions: (1) did reforestation with 35-year-old rubber tree plantation and 3-year and 5-year-old eucalyptus plantations enhance SOC accumulation up to 1 m depth? (2) How much has the conversion of forest into pasture changed the origin of SOC accumulated up to 1 m depth? (3) How much did the conversion of pasture into eucalyptus plantation or rubber tree plantation changed the origin of SOC accumulated up to 1 m depth? The first objective, related to question 1 was quantification of SOC stocks under different forest plantations and pasture to a depth of 100 cm. The second objective, related to question 2 was evaluation of the contribution of C_3 and C_4 derived C using natural abundance 50 years after converting forest into pasture; and the third objective related to question 3 was evaluation of the contribution of C_3 and C_4 derived C, 3 to 5 years after converting pasture into eucalyptus plantations and 35 years after converting pasture into rubber tree plantations.

2. Materials and methods

2.1. Site description

Soil samples were collected at the Santa Helena Farm and Mundial Farm in the municipality of Muriaé (21° 07′ 50″ S 42° 21′ 59″ W) in the southern area of Minas Gerais state, Brazil, within the Atlantic Rainforest Biome domain. The city's climate is tropical and classified as Aw according to Köppen's classification system. The average annual temperature is 22.9 °C and the annual precipitation is 1314 mm. The altitude is 201 m above the sea. Soils of both farms is an Ultisol (dystrophic Red-Yellow Argisol, Brazilian Classification System, Embrapa, 2013) or as Typic Hapludult (Soil Survey Staff, 2014).

The experimental area in this study was:

1. 3-year-old eucalyptus plantation;
2. 5-year-old eucalyptus plantation;
3. 35-year-old rubber tree plantation, with a 7 × 4 spacing between rows and plants, and this area was previously cultivated (around 50 years) with pasture. Fertilization was made during plantation with 30 g P_2O_5 and 30 g K_20 per plant. During the first year (3 times) after plantation, 30 g^{-1} plant of N was applied.
4. Secondary forest - had herbaceous, shrub and individuals of the upper canopy eliminated approximately 30 years ago, leaving smaller trees.
5. 50-year-old unfertilized pasture area composed by *Brachiaria decumbens*.

In both eucalyptus plantations trees were spaced 3 × 2.5 m between row and plants, respectively. The fertilization was conducted during plantation with rock phosphate (100 g plant^{-1}) and NPK 20-00-20 (50 g plant^{-1}). These areas were previously cultivated (around 50 years) with pasture.

The eucalyptus plantations with 3 years and 5 years old have distinct growth stages, which justify them being chosen for the study of soil C stock. 3 years old of eucalyptus plantation is characterized by fast development and high dry matter accumulation rates. Canopy growth in 3-year-old eucalyptus plantation is a major proportion of leaves and twigs; biomass roots growth is increasing and shows a high input o leaf litter, mostly leaves (Grove et al., 1996).

The 5-year-old eucalyptus plantation is characterized by a canopy closure, where foliar biomass is relatively stable and the formation of heartwood is a major part of the net primary productivity (Grove et al., 1996). According to these authors, during this stage, the exploration of soil volume by fine roots is high, and stems, branches and barks are the great proportion of litter fall.

No young rubber tree plantation was chosen, given that they were not fully developed and did not show significant inputs of plant residues in the soil. Thus, the contribution on soil C stock will be that of prior vegetation and not from the newly planted rubber tree. The 35-year-old rubber tree plantation was chosen because it was the most homogeneous and well developed plantation.

2.2. Soil sampling and analysis

Four plots (30 × 30 m) were defined in the center of each vegetable cover that were uniform in terms of soil homogeneity, slope, historical land use, density and tree age and were separated by at least 100 m. Trenches (1 × 1 × 1.5 m) were dug between the plant rows in each plot. The soil was sampled at six depths (0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm). These depth classes were chosen in accordance with the protocol used for a multicountry study on soil C sequestration in AFS (Haile et al., 2008; Saha et al., 2009; Gama-Rodrigues et al., 2010; Monroe et al., 2016).

Soil samples from each depth were air dried and passed through a 2-mm sieve and soil particle size was determined using the pipette method (Embrapa, 1997) (Table 1). The volumetric ring method was used to determine soil bulk density (Embrapa, 1997) (Table 1) and the SOC was determined by dry combustion in an automated elemental analyzer (CHNS/O analyzer). The following measurements were performed using the methods described in EMBRAPA (1997): pH was measured