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Original research paper

Soil organic carbon changes after deforestation and agrosystem establishment in Amazonia: An assessment by diachronic approach

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ABSTRACT

Deforestation and agrosystem establishment can alter soil organic carbon (SOC) stocks, leading to greenhouse gases emissions and fertility losses, however SOC response has great variability. In the humid tropics like the Amazonia biome, carbon inputs from agrosystems are rarely quantified and described, despite their major contribution to the SOC dynamics after deforestation.

We assessed SOC dynamics with repeated measurements in the layer 0–30 cm until five years after deforestation in a diachronic site in French Guiana, cleared with a fire-free method associated to large woody debris inputs. Three agrosystems were studied: one year maize/soybean rotation with disk tillage (DT) and without tillage (NT), and a mowed grassland (G). Aboveground carbon inputs from agrosystems were measured. In addition to SOC stocks assessment, we measured roots carbon stocks, and performed $\delta^{13}C$ measurements in grassland soil.

We found a transient SOC stock increase until 1.5 years after deforestation because of large woody debris inputs from deforestation method, but these C inputs were rapidly mineralized and poorly contributed to SOC stocks 5 years after deforestation.

SOC stocks in grassland did not differ from forest despite large hay exports. Thanks to large root-derived carbon inputs, C4-SOC stock in grassland was 10.4 t ha^{-1} 5 years after deforestation (18.7% of the SOC stock).

In annual crops, 5 years after deforestation, SOC stocks decreased on average by 18.6% compared to forest. SOC stocks did not differ according to soil tillage since aboveground carbon inputs were similar in DT and NT systems. Lower SOC stocks in annual crops compared to grassland is explained by lower carbon restitutions and by higher mineralization rate of organic matter.

1. Introduction

Net emissions of CO_2 due to deforestation were 4.04 Gt CO_2 yr^{-1} over the period 1991–2015 (Federici et al., 2015), contributing to anthropogenic greenhouse gases (GHG) emissions and thus to climate change. In the last decades deforestation occurred mainly in tropical regions and including Amazonia, driven by agricultural demand (Gibbs et al., 2010). The CO_2 emissions from deforestation are related to the vegetation burning, but soil organic carbon (SOC) stocks can also decrease following deforestation (Don et al., 2011; Guo and Gifford, 2002). At global scale, the contribution of SOC stock variation to GHG emissions from forest conversion to cropland is estimated to 16.5 ± 5.5% (Kim and Kirschbaum, 2015). In addition SOC loss from deforestation may decrease crop production after some years following deforestation, since nutrient and water cycles are strongly linked to the soil organic matter levels (Bationo et al., 2007; Lal, 2006).

Numerous studies reported SOC stocks changes after deforestation and agrosystem establishment in the tropics. If taking into account the whole tropics, SOC response to land-use change can be partly explained by biophysical factors like precipitation, temperature, and clay mineralogy, depending on meta-analyses (Don et al., 2011; Powers et al., 2011). But at the Amazonian biome scale, where biophysical factors are less contrasted, these latter explained poorly the SOC stocks changes after deforestation (Fujisaki et al., 2015b). There is a large consensus about the SOC stock decrease after conventional cropland establishment (Don et al., 2011; Powers et al., 2011), because of the decrease in

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litter inputs and increase in soil carbon mineralization rate (Tinker et al., 1996). Nevertheless, the magnitude of this soil carbon loss is subject to large uncertainties since management practices, especially carbon inputs by crop residues, are rarely measured in tropical studies, although carbon inputs to soil are a major determinant of SOC dynamics (de Moraes Sá et al., 2015; Luo et al., 2010; Warren Raffa et al., 2015). The effect of reduced tillage practices on SOC stocks following deforestation is unclear in Amazonian croplands (Fujisaki et al., 2015), however Maia et al. (2010) found that full tillage decreased SOC stocks compared to no tillage systems in Southwest Amazon. Results for grassland establishment after deforestation in the tropics diverge depending on studies. Some meta-analyses reported SOC loss (Don et al., 2011), other slight gains in SOC (Eclesia et al., 2012; Fujisaki et al., 2015b; Neill and Davidson, 2000; Powers et al., 2011). Again, the grassland management is scarcely known in the compiled studies, and current classifications poorly improve the analysis of SOC dynamics (Fujisaki et al., 2015b). Moreover, studies dealing with land-use change effect on SOC in the tropics were almost exclusively conducted by analyzing chronosequences (synchronic approach) (Don et al., 2011; Fujisaki et al., 2015b). In synchronic studies the spatial variability of soil properties (e.g. particle size distribution) and land-use history leads to uncertainties (Neto et al., 2010) and even bias (Costa Junior et al., 2013). Instead, diachronic approach is more accurate and powerful since it can capture effect of climate on SOC dynamics (Dimassi et al., 2014), but it was scarcely used in the humid tropics.

Fire-free deforestation is a promising technique that aims to reduce environmental impacts of deforestation. Compared to burning practices, grinding and mulching part of the forest vegetation reduces GHG emissions (Davidson et al., 2008) and soil erosivity (Denich et al., 2005), but increases short-term nutrient concentrations and water retention (Comte et al., 2012). However the effect of these practices on mid-term SOC storage was not studied in humid tropics (Perrin et al., 2014).

In this paper we analyzed the changes in SOC stocks after forest clearing without burning and agrosystem establishment, on a randomized complete block design experimental site (five years) in French Guiana. Deforestation was fire-free and induced large organic inputs. We aimed to compare the SOC dynamics between the previous forest, grassland system and two annual crop systems with and without tillage. Two major research questions arised from this study: (i) how large organic matter inputs from fire-free deforestation influenced SOC stock changes five years after deforestation; and (ii) how SOC response to deforestation was driven by land-use (grassland vs cropland) and management practices (effect of tillage and carbon inputs). The originality of this study in the tropical humid context lies in: (i) the intercomparison of three land uses (forest, grassland and crops; with two tillage practices) on the same site; (ii) the diachronic analysis of SOC stock changes, eliminating uncertainties from spatial heterogeneity of soils; and (iii) the detailed monitoring of agrosystems management after forest clearing, including aboveground carbon inputs.

2. Material and methods

2.1. Study site and soil sampling

The experimental site, called “Combi”, is an area of 2 ha located in French Guiana (5°17′55″N/52°55′01″W). The climate type is Ami in the Köppen-Geiger classification, annual temperature is 27.3 °C and mean annual rainfall is 2770 mm; dry season occurs from August through November. Natural vegetation of Combi is the sempervirent rainforest. Soils are classified as Hyperferralic Ferralsol (IUSS Working Group, 2007), they are characterized by a sandy-clayey texture and a high vertical drainage. Main characteristics of the forest soils from 0 to 30 cm depth are presented in Table 1.

The historical management of the site is summarized in Fig. 1. The site of Combi was deforested in October 2008, using a fire-free method, called « chop-and-mulch » (Kato et al., 1999; Perrin et al., 2014). Forest undergrowth (trees and stems smaller than 15 cm diameter) was grinded with an axis mulcher, residues (11.2 t C ha^{-1}, Perrin et al., 2014) were left on the soil surface. Timbers were removed and exported off the deforested area. In December-January 2009, soil was limed and tilled with disk harrow to 20 cm depth, fertilized first with 40.5 kg ha^{-1} of P_2O_5 and then with 25.5 kg ha^{-1} of N, P_2O_5 and K_2O, and cover plants (a mixture of grass and legumes) were sown. In October 2009, woody debris and cover plants were grinded with a forestry mulcher and incorporated into the 0–10 cm soil layer (Perrin et al., 2014). Carbon inputs to the soil following deforestation are presented in Table 2.

Three agrosystems were set up, with planting in December 2009: (i) grassland (G) of *Urochloa ruziziensis* (formerly named as *Brachiaria ruziziensis*), with two grass cut per year: one cut for grass export and one cut of regeneration with biomass restitution; (ii) disk tillage (DT) with maize/soybean rotation, with soil tillage by disk harrow down to 20 cm depth twice a year before planting, and with crop residues restitution; (iii) no-tillage (NT) maize/soybean rotation, without tillage. The NT system was characterized by direct seeding and a permanent dead mulch cover from crop residues, but without cover crop. All agrosystems were limed (1 t of powder dolomite ha^{-1} year^{-1}) and fertilized with NPK. Grassland received 50–60 kg of N, P_2O_5 and K_2O ha^{-1} year^{-1}, maize was fertilized with 140–173 kg of N, 76–80 kg of P_2O_5, and 76–80 kg of K_2O ha^{-1} year^{-1}, and soybean with 73–80 kg of P_2O_5, and 78–80 kg of K_2O ha^{-1} year^{-1}. Agrosystems were set up according to a randomized complete block design with four blocks of 10 × 20 m plots for each system. Forest soils were sampled before deforestation in September 2008, on the future experimental area, with 17 pits dug to 60 cm depth. Soil cores (0.05 m thickness × 0.10 m diameter) were collected down to 55 cm depth.

After deforestation, soils were sampled with a hand auger following a regular grid of 6 sampling points per plot, resulting in 24 sampling points per crop system for each field campaign. Soils were sampled with this design in November 2009, April 2010, November 2010, November 2011, November 2012, and November 2013. Soil cores (0.05 m thickness × 0.08 m diameter) were collected at 0–5, 5–10, 10–20 and 20–30 cm depth.

In November 2013, five years after deforestation, in three plots of each agrosystem, one pit was dug with a shovel down to 100 cm depth. Only one pit could be dug in each plot given the small size of the plot. One pit was also dug in the forest area on the edge of the deforested area. These pits were used to measure root carbon stocks and $\delta^{13}C$ values in grassland. On these pits, soils were sampled every 10 cm depth. Three to four kg of soils were sampled from three faces of the soil profile. Soil bulk density was measured every 10 cm by water method. Briefly, for each layer, a circular hole was dug; the collected soil was immediately weighed. The whole soil volume was measured with a plastic bag introduced in the hole and poured with water. An aliquot of soil was conserved to measure soil moisture at laboratory after 48 h at 105 °C.

2.2. Quantification of carbon inputs to soils

For the three agrosystems, aboveground biomass left on the soil and/or exported at each harvest was quantified, with two measurements per plot. For maize and soybean in DT and NT systems, areas of 3 and 2 m^2 respectively were sampled before harvest. For grassland system, 1 m^2 quadrats were sampled before each grass cut.

Plant samples were dried at 65 °C until constant weight then weighed and ground. C content of plant samples were measured by dry combustion (Thermoquest NA 2100 analyzer).