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Soil carbon and nitrogen dynamics as affected by land use change and successive nitrogen fertilization of sugarcane

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ABSTRACT

The land use change (LUC) and application of N fertilizers have potential to affect soil C and N dynamics and long–term C and N stocks. We aimed to evaluate the effects of the LUC from native vegetation (seasonal semideciduous forest) to sugarcane (*Saccharum* spp.) cultivation under successive annual N fertilizer applications on chemical and microbiological attributes of sugarcane–cropped soils. Two field trials were performed during three (Site 1) or four years (Site 2) in southeastern Brazil. Soil sampling was carried out in the following N treatments applied to the crop: control (N–unfertilized plots), organomineral fertilizer (100 kg ha^{-1} yr^{-1} N), and synthetic fertilizer (100 and 200 kg ha^{-1} yr^{-1} N). Soil samples from native vegetation located near each site were also taken, to serve as reference for studying LUC. For Site 1, successive application of N fertilizers on sugarcane managed under green cane trash blanketing system maintained the C and N dynamics and stocks in soil to conditions similar to those found before LUC. At Site 2, however, modifications in soil attributes caused by LUC were more impacting than the N fertilization management. Compared to synthetic N fertilizers, successive application of organomineral fertilizer did not improve the soil microbiological attributes as well as organic C and total N stocks. Lastly, successive high N input (200 kg ha^{-1} yr^{-1}, via synthetic fertilizer) promoted accumulation of mineral N deep in the soil profile, thus increasing potential losses through NO_3^- leaching.

1. Introduction

From a sustainable perspective, sugarcane (*Saccharum* spp.) is one of the best feedstocks for bioenergy production (Miller, 2010). Only during the last decade (2006–2016), the land area devoted to sugarcane in Brazil, the world's largest producing country, increased from 5.8 to 9.1 Mha (Conab, 2016). In addition, land under sugarcane cultivation (SC) in Brazil is expected to increase over the next decades due to the world growing demand for sugar and bioethanol (Goldemberg et al., 2014; Otto et al., 2016 Otto et al., 2016). Although land intensification could promote higher yield levels, the land use change (LUC) caused by sugarcane expansion is irrefutable and necessary to sustain the increased demand for renewable energy sources (Nassar and Moreira, 2013). Responsible for ~50% of the national sugarcane production, the Southeast region of Brazil has limited potential to expand onto native vegetation (NV), as natural ecosystems are protected by strict conservation laws imposed from the 1980s. Thus, while the direct deforestation of NV to SC was adopted in past decades in southeastern Brazil, primarily in the state of São Paulo, the most common chronological sequence of this conversion nowadays is crop or pastureland to SC (Adami et al., 2012; Egeskog et al., 2014 Egeskog et al., 2014).

Investigation on LUC effects related to chemical and microbiological soil attributes is essential to assess the sustainability of sugar and bioethanol production (Cherubin et al., 2015; Oliveira et al., 2016 Oliveira et al., 2016). Most of sugarcane–cropped area in Brazil are mechanically harvested under the green cane trash blanketing (GCTB) system, where the crop residues (dry leaves and tops) are left on the soil surface, thus promoting nutrient cycling. Although previous studies have argued that biofuel expansion onto natural ecosystems and pastureland could substantially increase net CO_2 emissions and reduce organic C (OC) stocks in soil (Creutzig et al., 2015; Gibbs et al., 2008; Oliveira et al., 2016), other authors reported that the conversion from pasture to SC (under GTCB system) in Brazil has potential to increase OC stocks through crop residues deposition (Cerri et al., 2011; Oliveira et al., 2016). However, in general, the sugarcane expansion area has induced the soil to net C sink in the last two decades (Egeskog et al., 2014).

Another important factor that may affect the maintenance of OC stocks but also the total N (TN) ones in soil is related to fertilizer management. The use of synthetic N fertilizers for biofuel crops has

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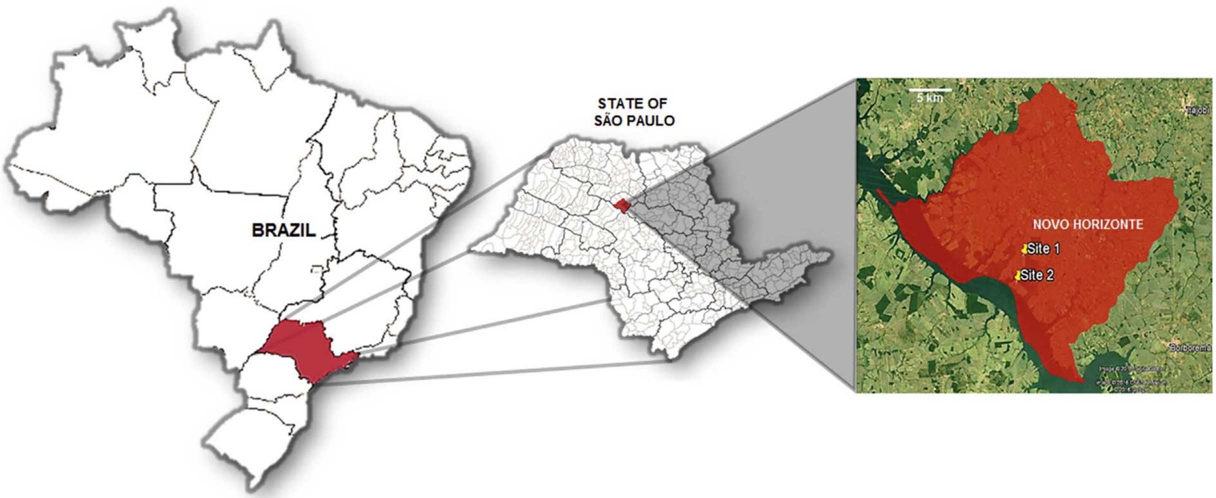

Fig. 1. Location of the two experimental sites under sugarcane cultivation in the state of São Paulo, southeastern Brazil.

given rise to controversy over the sustainability of bioenergy because of greenhouse gas (GHG) emissions (Creutzig et al., 2015; Crutzen et al., 2007; Erisman et al., 2010; Skocaj et al., 2013). While the sugarcane fertilization with synthetic N may favor C sequestration by increasing plant biomass production and crop residues deposition, excess N from fertilizer may favor microbial growth, thus leading to faster C and N mineralization (Paungfoo-Lonhienne et al., 2015; Mariano et al., 2016; Yeoh et al., 2016). This is congruent with some studies reporting depletion of OC and TN stocks in corn–cropped soil caused by long–term application of synthetic N fertilizers (Khan et al., 2007; Mulvaney et al., 2009). In contrast, several studies have shown that organic fertilizers increase OC and TN stocks (Ladha et al., 2011; Liu et al., 2013; Suman et al., 2009). However, the influence of synthetic and organic N fertilizers on C and N dynamics in soil is still debated (Olson, 2013; Stockmann et al., 2013). In Brazil, the N rate applied to sugarcane fields (60–120 kg ha^{-1} yr^{-1}) is significantly lower than other producing countries (Robinson et al., 2011). In addition to synthetic fertilizers, byproducts originated from the sugarcane industry (e.g., vinasse, press mud, and ash boiler) and organomineral fertilizers are also applied to the crop, which can greatly alter nutrient–cycling dynamics in the soil–plant system (Otto et al., 2016).

The application of organic, organomineral or synthetic N fertilizers can indirectly affect soil microorganisms by increasing mineral N (MN) availability, accelerating nutrient cycling or lowering soil pH through nutrient uptake by plants (Wardle, 1992). These effects in soil microorganisms can be measured using diverse indicators which quantifies its amount, activity and diversity through the following techniques: microbial biomass, soil respiration, and DNA extraction, respectively (Bünemann et al., 2006). While the use of synthetic fertilizers has been shown to have rapid and variable influence in soil, in which can promote mineralization of organic matter (stable fraction) at high N rates or increase OC stocks by plant biomass production, the usage of organic fertilizers has generally been shown to result in positive long–term effects (Leita et al., 1999; Parham et al., 2002; Witter et al., 1993). At the least, organic fertilizer application has been shown to return the soil to its initial conditions, that is, to its conditions preview the organic fertilizer application over the years, thus increase its resilience (García-Gil et al., 2004; Speir et al., 2003).

After application of synthetic N fertilizers on sugarcane cultivated under the GCTB system, part of the fertilizer–N is lost by volatilization (primarily from urea–based fertilizers), leaching, and denitrification, but most of the MN is immobilized to microbial biomass, while the remaining portion (20–40%) is taken up by the crop (Mariano et al., 2015). Although the fate of synthetic N fertilizers applied to sugarcane fields is relatively well known (Otto et al., 2016), studies reporting the influence of organic and organomineral fertilizers on chemical and microbiological soil attributes are limited to grain crops cultivated in temperate regions (Khan et al., 2007; Ladha et al., 2011; Mulvaney et al., 2009). Considering the global interest in sugarcane for sustainable bioenergy production, research approaching application of different N fertilizer sources is therefore required. In addition, *in situ* measurements of NO_3^- leaching (Ghiberto et al., 2015, 2009; Oliveira et al., 2000), NH_3 volatilization (Cantarella et al., 2008; Mariano et al., 2012), N use efficiency (Fortes et al., 2012; Vieira-Megda et al., 2015), N_2O emissions (Carmo et al., 2013; Signor et al., 2013), and crop response to N fertilization (Mariano et al., 2015; Otto et al., 2013) have been conducted in sugarcane fields throughout Brazil in GCTB systems over the last decade. However, most of these measurements were taken in a short time after fertilizer application, generally from a few weeks to one year. Thus, little is known about the effects of successive N fertilization on soil C and N dynamics and microbiological attributes.

Our objective was therefore to evaluate the LUC effects from NV to SC influenced by annual successive application of organomineral and synthetic N fertilizers, soil OC and TN stocks throughout the profile (0.0–1.0 m), as well as MN availability, N mineralization, and microbiological attributes in the top 0.2 m soil depth. We hypothesized that (i) the LUC to sugarcane under GCTB system, although broadly consolidated, affect negatively the soil OC and TN stocks, and (ii) compared to synthetic N fertilizer, successive application of organomineral fertilizer in sugarcane improve soil microbiological attributes.

2. Material and methods

2.1. Site description and experimental design

Two field trials were carried out in nonirrigated sugarcane–cropped areas in Novo Horizonte, SP, Brazil (Site 1: 21°30′34“S and 49°18′50“W; Site 2: 21°32′37“S and 49°19′28“W). Sites 1 and 2 were located ~4 km apart (Fig. 1). The climate at both sites is humid and tropical, with a dry winter and heavy rains during the summer. The mean annual temperature is 23.2 °C and the mean annual precipitation is 1134 mm yr^{-1} (29–yr average). The conversion of seasonal semidesciduous forest to cropland (sugarcane) occurred in the 1970s and 1990s at Sites 1 and 2, respectively. However, it was not possible to identify the exact year of this LUC. The sugarcane cultivar planted at Sites 1 and 2 was SP91–1285 (released by Copersucar) and CTC15 (released by CTC), respectively. At both sites, the soil is classified as Typic Hapludox (Soil Survey Staff, 2014). The agricultural history of the sites includes a long–term application of sugarcane vinasse (at a rate of 120 m^3 ha^{-1} yr^{-1} during 10 and 12 years at Sites 1 and 2, respectively)