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Soil carbon, nitrogen and phosphorus changes under sugarcane expansion in Brazil

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HIGHLIGHTS

- An explanatory approach to the responses of soil C, N and P to sugarcane expansion is provided.
- Conversion of pasture to sugarcane produces a net C emission of 1.3 Mg ha^{-1} yr^{-1} in 20 years.
- C emission is caused by the respiration of SOM from C4-cycle plants.
- ^{15}N signal mostly increased, indicating an accumulation of recalcitrant SOM under sugarcane.
- Biological pool accounting for more than 50% of the soil labile P in both land uses

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ABSTRACT

Historical data of land use change (LUC) indicated that the sugarcane expansion has mainly displaced pasture areas in Central–Southern Brazil, globally the largest producer, and that those pastures were prior established over native forests in the Cerrado biome. We sampled 3 chronosequences of land use comprising native vegetation (NV), pasture (PA), and sugarcane crop (SC) in the sugarcane expansion region to assess the effects of LUC on soil carbon, nitrogen, and labile phosphorus pools. Thirty years after conversion of NV to PA, we found significant losses of original soil organic matter (SOM) from NV, while insufficient new organic matter was introduced from tropical grasses into soil to offset the losses, reflecting in a net C emission of 0.4 Mg ha^{-1} yr^{-1}. These findings added to decreases in ^{15}N signal indicated that labile portions of SOM are preserved under PA. Afterwards, in the firsts five years after LUC from PA to SC, sparse variations were found in SOM levels. After more than 20 years of sugarcane crop, however, there were losses of 40 and 35% of C and N stocks, respectively, resulting in a rate of C emission of 1.3 Mg ha^{-1} yr^{-1} totally caused by the respiration of SOM from C4-cycle plants. In addition, conversion of pastures to sugarcane mostly increased ^{15}N signal, indicating an accumulation of more recalcitrant SOM under sugarcane. The microbe- and plant-available P showed site-specific responses to LUC as a function of different P-input managements, with the biological pool mostly accounting for more than 50% of the labile P in both anthropic land uses. With the projections of 6.4 Mha of land required by 2021 for sugarcane expansion in Brazil to achieve ethanol's demand, this explanatory approach to the responses of SOM to LUC will contribute for an accurate assessment of the CO_2 balance of sugarcane ethanol.

1. Introduction

Globally LUC associated with the expansion of biofuel production has impacts on SOM (Anderson-Teixeira et al., 2009; Don et al., 2011), the largest terrestrial carbon pool (Lal, 2004) and key to the accurate assessment of the CO_2 balance of energy crops (Djomo and Ceulemans, 2012; Fargione et al., 2008; Mello et al., 2014). Recent studies have assessed the impacts of converting native ecosystems or cropland into a range of biofuel crop production on soil organic carbon (SOC) dynamics, with attention to its ecosystem services (Anderson-Teixeira et al., 2009; Don et al., 2011; Frazao et al., 2013; Kwon et al., 2013; Zatta et al., 2014). Roughly one-third of the global ethanol fuel production has been provided from Brazilian sugarcane, with small contributions from other Latin America countries (Goldemberg et al., 2014).

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The recent expansion of bioenergy crops in Brazil is driven by an increased demand for ethanol with more than 3 Mha of new sugarcane areas established between 2000 and 2010 in the Central–Southern Brazil (Adami et al., 2012). It is estimated that this region has concentrated 99% of the recent sugarcane expansion in Brazil in recent years (Hernandes et al., 2014; Sparovek et al., 2009), and approximately 70% of this expansion came from pastures (Adami et al., 2012). More than 6.4 Mha of additional sugarcane land will be required to meet the Brazilian demand for ethanol in 2021, with the potential to meet global demand for renewable fuels (Goldemberg et al., 2014). This intensification of sugarcane expansion can result in initial decreases in SOC stocks when pastures are converted into sugarcane (Mello et al., 2014) or from native ecosystems to sugarcane (Fargione et al., 2008), even though native transitions directly into sugarcane have historically accounted for less than 1% of the sugarcane expansion in Brazil (Adami et al., 2012).

Although we can accurately assess the effects of LUC on soil carbon stocks with the recent publication of LUC factors for sugarcane production in Brazil (Mello et al., 2014), the SOM dynamics for old and new organic matter in these areas of expansion remain unclear. Stable isotopes of C and N have been used to better understand C and N dynamics in studies on the effects of long-term sugarcane production (Dominy et al., 2002; Rossi et al., 2013) and of different sugarcane cropping systems (Pinheiro et al., 2010; Rachid et al., 2012). The ^{13}C signal found in soil reflects changes in plant cover and SOM inputs, therefore isotope techniques have been used to determine LUC effects on SOM cycling (Vitorello et al., 1989). Besides being the only primary source of nitrogen in unfertilized soils (Schulten and Schnitzer, 1997), SOM is often the major storehouse of soil phosphorus, accounting for 30 to 65% of total P in soils (Shen et al., 2011), both of which are primary plant nutrients. Nitrogen is the mineral element required in the largest amounts for plants (Miller and Cramer, 2004), and LUC affects N cycling, distribution and storage in soils, modifying the inputs and outputs via the decomposition of organic matter (Yan et al., 2012; Zhang et al., 2013). Phosphorus availability to plants in highly weathered soils of the tropics is limited by the pronounced P-sorption capacity of these soils (Fontes and Weed, 1996; Lawrence and Schlesinger, 2001). In these tropical soils the pools of organic P and mineralization of SOM are critical for plant productivity (Cross and Schlesinger, 1995), and the management of soil organic resources has been considered extensively for moderating P availability (Fonte et al., 2014; Nziguheba et al., 1998).

Land use transitions in sugarcane expansion areas are therefore expected to affect the abundance of stable isotopes of C and N in SOM, namely increasing ^{13}C and ^{15}N signals, which reflect the dynamics for old and new organic matter in these areas and better explain SOC stock responses to LUC. In addition, such changes in SOM could impact the storage of N and labile P pools given the close linkage between them and SOM dynamics. In this study we addressed the effects of the most common land use sequence in areas of sugarcane expansion, i.e. native vegetation – pasture – sugarcane, on the soil carbon, nitrogen, and labile phosphorus pools. Specifically, we wanted: (1) to compare SOM levels among land uses and evaluated their effect on the biologically-associated labile P pool, (2) to assess SOM humification degree as a function of the land use by examining the natural abundance ^{15}N composition, (3) to investigate the impact of LUC on carbon, nitrogen and phosphorus storage on an equivalent soil mass basis, and (4) to investigate the dynamics of new C inputs from C4 plants entering into pasture and sugarcane soils.

2. Material and methods

2.1. Description of the study sites

The study was carried out in the main sugarcane producing region in the world, Central-Southern Brazil. Three study sites were identified representing the Northern, Center, and Southern parts of the Brazilian sugarcane growing region, including the areas where sugarcane expansion is occurring from pastures: Lat_17S, located in the city of Jataí, Southwestern region of Goiás state (17°56′16″S, 51°38′31″W) with a mean altitude of 800 m; Lat_21S, located in the city of Valparaíso, West region of São Paulo state (21°14′48″S, 50°47′04″W) with a mean altitude of 425 m; and Lat_23S, located in the city of Ipaussu, South region of São Paulo state (23°05′08″S, 49°37′52″W), with a mean altitude of 630 m (Fig. 1).

The study sites classified as per Köppen were: Awa (mesothermal tropical) at Lat_17S, where the mean annual temperature (MAT) is 24.0 °C and the mean annual precipitation (MAP) is 1600 mm; Aw (humid tropical) at Lat_21S, where MAT is 23.4 °C and MAP is 1240 mm; and Cwa (tropical) at Lat_23S, where MAT is 21.7 °C and MAP is 1470 mm. All three sites present the rainfall season concentrated in the Spring–Summer (October to April) and the dry season in the Autumn–Winter (May to September).

The soils of the study sites were classified according to Soil Survey Staff (2014) (Table 1). The three sites were primarily well-drained and highly weathered surfaces, typical of tropical wet conditions. In each study site we identified a chronosequence of land use for: native vegetation (NV), pasture (PA), and sugarcane crop (SC). In order to minimize the effects of climatic, topographic and edaphic variations, the three land uses were always located in adjacent areas. Table 1 shows the soil bulk density and clay contents in the 0–10 cm, 10–20 cm, and 20–30 cm soil layers, besides the information on land use and management for each field site which includes the type and duration of each land use, as well as nutrient inputs. Briefly, the NV at Lat_17S comprises the Cerradao forest formation, while at Lat_21S and Lat_23S NV comprises a transition between the Atlantic forest and Cerrado vegetation. LUC from NV to PA happened in 1980 at Lat_17S and Lat_21S, and in 1979 at Lat_23S. PA areas differed from each other in the stocking rate: PA at Lat_17S supports 1.5 animal unit (AU) ha^{-1}; PA at Lat_21S supports around 2 AU ha^{-1}; and PA at Lat_23S supports around 1 AU ha^{-1} along the year. The SC was established over part of PA in 2009 at Lat_17S, in 2010 at Lat_21S, and in 1990 at Lat_23S. The nutrient inputs in SC differed among the sites, with annual inputs of mineral P at Lat_21S and high amounts of organic fertilizers at Lat_23S (Table 1).

2.2. Soil sampling and analyses

The soil sampling was carried out in January 2013. Sampling for each land use site consisted of a 2.25 ha grid with 9 sampling points spaced 50 m apart, composing 27 sampling points for each study site, or 81 sampling points in total. Within a radius of 6 m around each sampling point, 12 subsamples were collected from the 0–10 cm, 10–20 cm, and 20–30 cm soil layers using a soil Dutch auger, and combined (resulting in one sample for each soil depth in each sampling point). Samples were dry-sieved and milled to pass through a 2 mm sieve followed by drying (50 °C) prior to phosphorus extractions. For carbon and nitrogen concentration and isotope composition measurements the samples were ground and sieved to 0.150 mm.

Organic carbon and total nitrogen were determined by dry combustion on elemental analyzer — LECO® CN-2000 (furnace at 1350 °C in pure oxygen). Isotope composition of C and N was determined by using a Thermoquest-Finnigan Delta Plus isotope ratio mass spectrometer (Finnigan-MAT) interfaced to an Elemental Analyzer (Carlo Erba). Isotope ratios are expressed in the classical δ-notation with respect to the Vienna Pee Dee Belemnite (V-PDB) standard. Reproducibility of the determinations is better than 0.2‰ for δ^{13}C and δ^{15}N.

Plant- and microbe-available “labile” soil P (P-lab) was used to investigate the effects of sugarcane expansion on P cycling due to the strong P-sorption capacity of the soils studied. Inorganic P-lab here is considered the amount of inorganic P extracted by resin and sodium bicarbonate 0.5 mol L^{-1} (Hedley et al., 1982). The organic P-lab was obtained by taking the difference between the total and inorganic P from sodium bicarbonate extract, after digestion by ammonium