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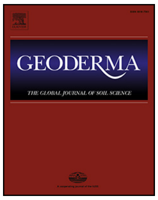

Soil physical quality response to sugarcane expansion in Brazil☆

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ABSTRACT

Globally, the rate of land-use change (LUC) is increasing rapidly to support biofuel feedstock production. In Brazil, sugarcane (*Saccharum officinarum*) expansion to produce ethanol is displacing degraded pastures. Intensive mechanization for sugarcane production, could impact soil physical quality in these areas. We evaluated a typical LUC sequence (i.e., native vegetation–pasture–sugarcane) on soil physical quality at three sites in the central-southern region of Brazil. The soil physical properties evaluated through on-farm and laboratory soil analyses were: bulk density, degree of compactness, macroporosity, microporosity and total porosity, water-filled pore space, indexes of soil water storage and aeration capacity, soil resistance to penetration, field-saturated hydraulic conductivity and stability structural index. Calculations of mean weight diameter for the soil aggregates and soil physical quality ratings from a visual evaluation of soil structure (VESS) were also included in this study. From those data we defined a minimum dataset for calculating an additive soil physical quality index (SPQI). Long-term conversion from native ecosystems to pasture increased soil compaction (i.e., higher bulk density, degree of compactness and resistance to penetration values), decreased aeration porosity and water hydraulic conductivity, and consequently, created an unbalanced ratio between water- and air-filled pore space in the soil. Based on our SPQI, the soil's capacity to perform its physical functions decreased from 90% under native vegetation to 73% under pasture. Land-use change from pasture to sugarcane induced slight soil physical quality degradation, in which soil function was 68 and 56% of capacity. Overall, soil physical quality decreased under sugarcane fields, due to decreases in soil porosity, aeration and water hydraulic conductivity as well as increases in soil penetration resistance, structural degradation and erosion risk. Tillage operations performed during the sugarcane replanting (~5 years) had a short-term positive effect on soil physical quality, although over time it further decreased the resistance to erosion and structural degradation. Therefore, to convert degraded pasture to sugarcane in a sustainable manner, the soils should be managed in ways that increase the soil organic matter and minimize compaction. These actions are needed to prevent further soil physical quality degradation and to improve both economic and environmental sustainability of sugarcane ethanol production.

1. Introduction

Increasing global demand for biofuel has promoted the intensification of LUC around the world, imposing concerns about soil physical quality degradation and its negative implications on ecosystem function (Gasparatos et al., 2011; Fu et al., 2015). Brazil is the largest sugarcane ethanol producer in the world, having increased from 5.8 to 9.0 Mha between 2005 and 2015 (Companhia Nacional de Abastecimento – Conab, 2015). To meet projected (2021) domestic supplies for ethanol in Brazil, an additional 6.4 Mha of sugarcane is required (Goldemberg et al., 2014).

Historically sugarcane expansion has been concentrated in central-southern Brazil, with 70% of this expansion occurring in degraded

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pasturelands (Adami et al., 2012). The development of Brazilian agriculture has seen extensification of pasture into native vegetation with poor management practices. This has resulted in loss of soil organic carbon (SOC) and soil fertility (Mello et al., 2014; Franco et al., 2015a; Cherubin et al., 2015a). It is estimated that 70% of Brazilian pasturelands are degraded or in the process of being degraded (Dias-Filho, 2014). The vast area of degraded pasture in Brazil, coupled with opportunities for improvements in current ranching practices, could provide enough land for sugarcane production to meet the projected demand for ethanol, while still meeting the domestic demand for other ecosystem services (Lapola et al., 2010; Goldemberg et al., 2014).

In comparison to pasture, sugarcane production requires intensive mechanization resulting in changes to soil physical properties and related processes. Soil tillage is used to incorporate lime and fertilizer when sugarcane is first established, and again at approximately five-year intervals when sugarcane yields begin to decrease and it is replanted. With the recent shift to mechanized harvesting, intensive machinery traffic may be contributing to soil physical degradation in these areas. Studies have shown increased soil bulk density and soil strength (Baquero et al., 2012; Bangita and Rao, 2012; Souza et al., 2014, 2015), with decreases in soil porosity, aeration, aggregation, water infiltration and available water in many sugarcane fields (Braunack and McGarry, 2006; Castro et al., 2013; Franco, 2015b; Hunke et al., 2015b).

Soil physical quality degradation has adverse impacts on root growth (Otto et al., 2011; Baquero et al., 2012; Souza et al., 2014, 2015), often limiting uptake of water and nutrients, thus decreasing sugarcane yields (Bangita and Rao, 2012; Souza et al., 2014). Decreased sugarcane productivity also decreases atmospheric CO_2 uptake by above and belowground biomass, resulting in lower organic C inputs and a gradual depletion of SOC (Franco et al., 2015a). Decreasing soil physical quality may also reduce ecosystem functioning (Fu et al., 2015), by accelerating soil C turnover (Six et al., 2000), decreasing SOC stocks (Mello et al., 2014; Franco et al., 2015a) and increasing CO_2 emissions (Ball, 2013; Silva-Olaya et al., 2013). In terms of biogeochemical processes, soil compaction reduces air-filled porosity favoring denitrification (N_2O emissions) and methanogenesis (CH_4 emissions) (Ball, 2013). Runoff and soil erosion risks increase because physically degraded soils have lower water infiltration rates (Hunke et al., 2015a, 2015b) and thus contribute sediment, nutrients, and pesticides to surface waters (Gucker et al., 2009; Hunke et al., 2015a,b). Furthermore, soil compaction can also modify or destroy native biological habitats, resulting in loss of biodiversity and ecosystem function (Benton et al., 2003).

Although many technical papers have been published, LUC effects on soil physical quality associated with sugarcane expansion in Brazil are still poorly documented. We conducted an on-farm study in the largest sugarcane-producing regions of Brazil to: i) quantify effects of the primary LUC sequence associated with sugarcane expansion (i.e., native vegetation to pasture to sugarcane) on soil physical properties, and ii) integrate the soil physical indicators of soil degradation into an additive index for assessing LUC impacts on soil physical functioning. We hypothesized that the LUC from native vegetation to pasture and then to sugarcane was resulting in continuous degradation of soil physical quality that could be detected by computing an overall soil physical quality index (SPQI).

2. Material and methods

2.1. Field sites and experimental design

The study was carried out in central-southern Brazil (Fig. 1) at three representative sites: i) Lat_17S: located near Jataí city in the southwestern region of the Goiás state which is currently the most important region for sugarcane expansion in Brazil; ii) Lat_21S: located near Valparaíso city in the western region of the São Paulo state, a transition area between traditional and new sugarcane production areas, and iii) Lat_23S: located near Ipaussu city in the south-central region of the São Paulo state, which represents the traditional sugarcane production areas of Brazil. Rainfall at all three sites is concentrated in the spring and summer (October to April), while the dry season is in the autumn and winter (May to September). Additional climate characteristics for each site are presented in Cherubin et al. (2015a). The soils at all three sites, classified as Oxisols, Ultisols and Alfisols and thus representing more than 70% of the Cerrado region (Lopes, 1984), are characterized by highly weathered minerals (Ki and Kr weathering indexes have values <2.0), typical of Brazilian tropical soils. The clay fractions were predominantly 1:1 minerals (kaolinite), Fe oxides (goethite, hematite) and Al oxide (gibbsite). Additional classification criteria, textural classes, anticipated SOC content, and drainage status for each site, as outlined by the USDA Soil Survey Staff (2014), are presented in Table 1.

A chronosequence was sampled at each site representing the most common LUC sequence in central-southern Brazil (native vegetation–pasture–sugarcane). Adjacent land-use areas were sampled to minimize uncontrolled factors. The land use history and the management practices for each site are presented in Table 1.

2.2. Sampling and soil physical measurements

Soil sampling was carried out in January 2014. At each land use (i.e., native vegetation, pasture and sugarcane) soil samples were collected using a consistent grid pattern composed of nine sampling points spaced 50 m apart, providing a total of 27 sampling points for each site (i.e., total of 81 sampling points for the three sites). At each sampling point, a small trench ($30 \times 30 \times 30$ cm) was opened to collect disturbed and undisturbed soil samples from the 0–10, 10–20 and 20–30 cm layers, providing a total of 243 soil samples for soil physical analyses. Although root systems of tropical pastures and sugarcane can reach deeper soil layers, we limited our assessment to 30 cm because most of roots are concentrated in this layer (Ball-Coelho et al., 1992; Kanno et al., 1999) and this is the zone where more significant soil physical property changes are induced by land use and management practices. The sampling points for each land use were positioned in representative locations within the total area sampled. In native vegetation areas we avoided sampling close to ant or termite nests, burrows of wild animals and big trees. In pasture areas, which were continuously and uniformly grazed, our major caution was to avoid sampling on the preferential cattle trampling paths, where the soil is much more compacted. Except at Lat_17S where the soil had been recently tilled for sugarcane replanting, all sampling points in sugarcane fields were located within the inter-row position, which is homogeneously tracked during harvest operations.

Measurements of soil resistance to penetration (SRP) were taken around the soil sampling trenches to a depth of 30 cm using a digital penetrometer (PenetroLOG®). Five replicates were used to compute an average value for each sampling point. Field-saturated hydraulic conductivity (K_{fs}) was measured using the 'simplified falling-head' method proposed by Bagarello et al. (2004) and later used by Keller et al. (2012). Three replicate K_{fs} measurements for each sampling point were made using steel cylinders (height 15 cm × internal diameter 15 cm), inserted 8 cm into the soil and 330 ml of water applied according to Keller et al. (2012).

In the laboratory, disturbed soil samples were used to determine particle size using the hydrometer method (Gee and Or, 2002). The undisturbed soil samples were weighed (initial soil water content), saturated for 48 h by gradually raising the water level in a tray and weighed again. Soil water content at -6 kPa and -10 kPa water potentials were determined using tension tables similar to those described by Ball and Hunter (1988). The soil samples were then dried at 105 °C for 48 h and weighed again. Bulk density (BD, Mg m^{-3}) was calculated by dividing the soil dry mass by volume of the cylinder. The maximum bulk density (BD_{max}, Mg m^{-3}) was estimated using a pedotransfer function