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Research paper

Tensile strength and organic matter fractions in aggregates of a grass-covered mined soil under early stage recovery

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ABSTRACT

Several physico-chemical attributes are usually selected to evaluate the quality of mined soils under a process recovery. Although tensile strength and organic matter densiometric fractions extracted from aggregates are consolidated indicators of quality of agricultural soil, these attributes are rarely monitored in mined soils. We hypothesized that combining tensile strength, stability of aggregates and organic matter fractionation in free light and occluded light fractions is a potential strategy to detect effects of the root system of different plant species on soil quality. Therefore, we aimed to identify the most suitable plant species for promoting the recovery of soil quality, mainly with respect to soil structure improvement. The study was carried out in a coal mining area located in Candiota/Rio Grande do Sul State, Brazil. The evaluated plant species were *Hemarthria altissima*, *Paspalum notatum* cv. Pensacola, *Cynodon dactylon* cv. Tifton, and *Urochloa brizantha*. Roots improved soil structure by disrupting highly compacted soil aggregates caused by compression due to traffic of heavy-machinery during the topographic recomposition of the area. Based on the higher root density of *Urochloa brizantha* and consequently greater potential to improve soil structure and quality, our work strongly recommends the adoption of this plant species as a strategy to accelerate the recovery of the mined soil. Correlation of total organic carbon and carbon in densiometric fractions (free and ocluded light) with other soil/plant attributes was not clear, most probably due to the incipient stage of recovery of the soil. Therefore, these attributes were not efficient as indicators of soil quality at this point time. Our study highlighted that interpretation of non-mined soil attribute correlations cannot be directly transferred to mined soils, reinforcing the need to assume constructed soils as a new system, where monitoring of soil attributes in the long-term is key to anticipate improvement of soil quality.

1. Introduction

The recovery of mined soils can take decades or centuries and does not necessarily mean the restoration of edaphic conditions prior to mining (Mukhopadhyay et al., 2013). Mining processes, topographic recomposition of the mined area, soil profile reconstruction and intensive mobilization of surface soil horizons are certainly the main aspects defining the common characteristics of mined soils, such as severe degradation, poor structuration and low organic matter (OM) content (Krummelbein and Raab, 2012; Zhang et al., 2015; Stumpf et al., 2016a). Particularly, low OM levels in mined soils can be attributed to accelerated OM degradation and dilution (along the new soil profile), since the A-horizon is usually mixed with subsurface horizons to constitute the top soil of the newly reconstructed profile (Rethman, 2006; Sheoran et al., 2010; Maharana and Patel, 2013).

According to Mosebi (2010), coal mined soils in South Africa are severely compacted by heavy machinery, mainly in the top 0.30 m of the soil profile. Stumpf et al. (2016a) observed persistence of high soil compaction in a coal mined soil in Brazil, especially of subsurface layers, even after 103 months of revegetation. The authors detected aggregates formed by compression between 0.10–0.30 m depth, where roots from the cultivated grasses were incipient or absent. On the other

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hand, disintegration of the compacted layer and formation of new structural units due to the concentration of roots was observed within 0.00–0.10 m.

Soil compaction in coal mined areas often limits vegetation establishment, retarding soil restructuring (Rethman, 2006). In the same direction, Stumpf et al. (2016b) observed in the 0.10–0.20 m layer of a coal mined from Brazil persistence of high bulk density, low macropore percentage and low OM content although high root density was obtained by cultivation of *Urochloa brizantha* up to 103 months. The authors attributed their results to the incipient interrelations of the root system with the edaphic fauna of the degraded soil.

Long-term experiments are essential for monitoring the quality of mined soils. In the short and medium terms, the consolidation of grasses along with the lower soil disturbance, a gradual improvement in the capacity and intensity soil properties is expected, until the system reaches a new state of equilibrium in the long term (Reichert et al., 2016).

Several physico-chemical attributes are usually chosen for evaluating the quality of mined soils under recovery, such as particle size analysis, bulk density, total pore volume, stability of water-stable aggregates, weighted average diameter of aggregates, pH and OM content (Ussiri and Lal, 2006; Wick et al., 2009; Maharana and Patel, 2013; Stumpf et al., 2014; Zhang et al., 2015). On the other hand, although tensile strength and OM densiometric fractions extracted from aggregates are consolidated indicators of quality of agricultural soils, these attributes are hardly monitored in mined soils (Roscoe and Buurman, 2003; Ibarra et al., 2005; Abid and Lal, 2009; Ferreira et al., 2011; Santos et al., 2013; Abdollahi et al., 2014).

Soil tensile strength (TS) refers to the energy required to break the aggregates in smaller parts, which may translate to ability of roots to penetrate the soil (Ibarra et al., 2005). Soil moisture (Ley et al., 1989; Causarano, 1993), percentage of clay (Abid and Lal, 2009; Ferreira et al., 2011) and organic carbon content (Tormena et al., 2008; Guimarães et al., 2009) are one of the main drivers governing TS.

The association of organic carbon with mineral particles promotes the formation of stable aggregates and consequently prevents OM decomposition by its physical protection into the aggregates (Six et al., 2004; Schmidt et al., 2011; Wiesmeier et al., 2012). Therefore, total organic carbon stocks, distribution and stability of aggregates are usually sensitive to changes of soil/plant management systems and have been used as reliable indicators of soil quality (Eerd et al., 2014; Reichert et al., 2016; Lazicki et al., 2016; Merante et al., 2017; Trigalet et al., 2017).

After entering the soil, the transformation and oxidation of large organic fragments by its decomposers to smaller and more soluble and reactive molecules facilitates its interaction with soil minerals and its incorporation into aggregates, hampering further decomposition of the organic materials (Lehmann and Kleber, 2015). Therefore, the structure and especially the soil texture seems to play an important role on the preservation of carbon against degradation, where soils with finer texture may favor soil aggregation and carbon occlusion and consequently its protection against decomposition (Zinn et al., 2007; Zotarelli et al., 2007; Andruschkewitsch et al., 2013). In this way, less protected OM fractions are usually more sensitive to changes in soil quality than more protected fractions and the unfractionated OM, especially in short-term analysis.

In this context, we hypothesize that combining tensile strength, stability of aggregates and OM fractionation in the free light fraction and occluded light fraction is a potential strategy to detect effects of the root system from different plant species on mined soil quality. Finally, we aimed to identify the most suitable plant species for promoting the recovery of mined soils quality, mainly with respect to soil structure improvement.

2. Material and methods

2.1. Study area

The study was conducted in a coal mining area under concession of Riograndense Mining Company (CRM), located in Candiota/Rio Grande do Sul State, Brazil (31° 33′ 56″ S and 53° 43′ 30″W).

The main stages involved in the strip mining coal extraction process and the subsequent topographic recomposition of the mined area are: a) removal of the A, B and C horizons of the natural soil, which are transported by truck to cover the previously topographically leveled area; b) removal of saprolite and rocks (overburden) with a large dragline excavator; c) extraction of the coal seams; d) placement of the overburden spoils to fill the excavation produced by the previous strip, which are leveled by bulldozers for topographic recomposition; e) to finish the landscape restoration of the area, the natural soil A horizon (and B and C horizons) removed during stage (a) are deposited, and revegetated, thus creating the “constructed minesoil” (Stumpf et al., 2016a).

The soil was constructed in early 2003 and the soil layer placed over the overburden came mainly from the B horizon of the natural soil of the pre-mined area, a Rhodic Lixisol (IUSS, 2014), with the high clay content (465.50 g kg^{-1} clay), dark red color (2.5 YR 3/6) and lower OM content (11.5 g kg^{-1}) than A horizon (21 g kg^{-1}).

The experiment with different plant species (grasses and legumes) was installed in November/December 2003, using 20 m^2 (5 m × 4 m) plots, in a randomized block design with four replications. Due to the severe compaction caused by the intense movement of machinery during the soil construction (trucks loaded with 20 Mg of soil and Caterpillar D8T model bulldozer with 38 Mg mass, 259 kW gross power, with length and width of track on the ground of 3.20 m and 0.56 m per shoe, respectively, and ground contact area of 3.6 m^2), the soil was chiseled with a bulldozer to a depth of approximately 0.15 m. Then the area received dolomitic limestone equivalent to 10.4 Mg ha^{-1}effective calcium carbonate rating and 900 kg $ha^{-1}$of a 5-20-20 fertilizer (45 kg N, 180 kg P_2O_5, and180 kg K_2O), based on results obtained by soil testing. Annually, all plots of the experimental area also received 250 kg ha^{-1} of a 5-30-15fertilizer (12.5 kg N, 75 kg P_2O_5, and 37.5 kg K_2O) and 250 kg ha^{-1} of ammonium sulfate.

Perennial plant species were implanted, including grasses and legumes (*Lotus pedunculatus* cv Makú), in November/December 2003; however, the legumes did not thrive in the area, mainly due to adverse weather conditions in 2003/2004 and 2004/2005 growing seasons. Thus, the evaluated treatments were composed only of the following grasses: *Hemarthria altissima* (15 cuttings m^{-2}), *Paspalum notatum* cv. Pensacola (50 kg of seed ha^{-1}), *Cynodon dactylon* cv. Tifton (15cuttings m^{-2}), and *Urochloa brizantha* (10 kg of seed ha^{-1}).

Nevertheless, according to Stumpf et al. (2017), a compacted zone below 0.10 m layer was observed after 103 months of revegetation, as indicated by bulk density values higher than 1.40 Mg m^{-3}, macroporosity values lower than 0.10 $m^3 m^{-3}$, and penetration resistance values higher than 2 MPa (Table 1), which are considered restrictive for most agricultural crops in clayey soils (Reichert et al., 2009; Otto et al., 2011; Baquero et al., 2012). Additionally, the efficiency or residual effect of the liming performed in 2003, indicated by pH, base and aluminum saturation was still observed 103 months after the beginning of the experiment, especially in the 0.00–0.10 m (m) layer (Table 1). However, the low soil pH, low base saturation and the high aluminum saturation values in the 0.20–0.30 m layer possibly indicate acid mine drainage, which could be attributed to the presence of overburden in some soil monolith replicates (Table 2).

2.2. Soil sampling

In July 2012 disturbed samples were collected, with a shovel blade to avoid structure disruption, in the 0.00–0.10 m, 0.10–0.20 m, and