Revista
Brasileira de
Ciência do Solo

Division - Soil Use and Management | Commission - Soil Pollution, Remediation and Reclamation of Degraded Areas

Reclamation of a Degraded Coal-Mining Area with Perennial Cover Crops

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ABSTRACT: Studies addressing the potential of grass roots in improving the structural quality of constructed minesoils are not frequent in the literature, although they are essential for understanding the re-establishment of soil functions in the environment. The objective of this study was to quantify the root attributes of the species *Urochloa humidicola*, *Panicum maximum*, and *Urochloa brizantha* and relate them to the physical properties of a constructed minesoil in reclamation of an area degraded by coal mining. The study was performed in a field experiment in a coal mining area located in southern Brazil. Soil samples were collected, five years after experiment installation, to determine bulk density, macroporosity, distribution of water stable aggregates expressed in different size classes, mean weight diameter of water stable aggregates, and organic carbon content, as well as for chemical characterization. Root sampling was performed by the monolith method to a depth of 0.30 m. Results confirm the hypothesis that the root system of the perennial grasses studied positively contributes to recovery of the constructed minesoil in the 0.00-0.10 m layer after 58 months of revegetation. The higher percentage of large aggregates, higher bulk density, and lower macroporosity in the subsurface indicate the presence of degraded layers, negatively influencing the development of the grass root system. *Urochloa brizantha* exhibited the largest root matter in the surface layer, influencing the breakdown of the large and cohesive aggregates, transforming them into smaller crumbly aggregates. In the 0.10-0.20 m layer, *Urochloa humidicola* showed greater volume and root length in relation to other species; nevertheless, changes in soil physical properties were not observed, showing that the time span of the root growth of the species was not sufficient to provide improvements in the subsurface layers.

Keywords: minesoil, monoliths, compaction.

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Received: December 1st, 2015
Approved: August 8, 2016

How to cite: Pauletto EA, Stumpf L, Pinto LFS, Silva TS, Ambus JV, Garcia GF, Dutra Junior LA, Scheunemann T, Albert RP. Reclamation of a Degraded Coal-Mining Area with Perennial Cover Crops. Rev Bras Cienc Solo. 2016;40:e0150482.

DOI: 10.1590/18069657rbcs20150482

INTRODUCTION

A vital component in exploitation of mineral resources is recovery of areas that have been degraded by the mining process, especially in the case of surface mining, which has major impacts on soil and landscape (Yada et al., 2015) due to the removal of vegetation cover and layers of soil and underlying rocks (Mukhopadhyay et al., 2013), resulting in total change of the soil profile (Stumpf et al., 2014).

Topographic recomposition and construction of a new soil profile results in a much different environment than the original soil. A constructed minesoil is usually compacted by excessive machine traffic, which results in inadequate physical conditions for plant growth and development (Lunardi Neto et al., 2008; Wick et al., 2009; Sheoran et al., 2010; Borůvka et al., 2012; Stumpf et al., 2014; Sena et al., 2015), as well as a decrease in the biodiversity of soil fauna (Oliveira Filho et al., 2014) and carbon losses due to mechanical mixing of soil horizons (A, B, and/or C) during the operations of removal, transport, and placement of the soil (Ussiri and Lal, 2005; Leal et al., 2015). In addition to these impacts, in mine waste piles derived from coal processing (usually enriched in pyrite), the process of soil aggregation and structuring by the root system of cover crops can promote input of oxygen and water and increase the development of acid mine drainage in the reclaimed area (Quiñones et al., 2008; Campaner and Luiz-Silva, 2009; Costa and Zocche, 2009; Inda et al., 2010; Daniels and Zipper, 2010; Moura, 2014)

Reclamation of a mined area should return a degraded ecosystem to a non-degraded condition, which may be different from the original environment (Ibama, 2011). In the case of constructed minesoils, recovery of the ecosystem occurs through revegetation by the addition of organic material and consequent improvements in soil physical, chemical, and biological properties, which should result in increased stability of aggregates and reduced erosion (Akala and Lal, 2001; Sourkova et al., 2005; Onweremadu, 2007; Zhao et al., 2013; Mukhopadhyay et al., 2014; Zhang et al., 2015). On the other hand, if soil properties are modified by the presence of plant roots (Gregory, 2006) the quality of these properties can also influence their development (Lima et al., 2013).

The study of the root system of plants in the field is helpful to agronomic science because it quantifies the changes imposed on the soil physical environment through their growth and continuous renewal (Neves and Medina, 1999; Lima et al., 2012). However, studies addressing the potential for grass roots in changing the structural quality of minesoils are lacking.

Over the past 30 years, grasses of the *Urochloa* genus have achieved great economic importance in Brazil (Valle et al., 2009); when used in a crop-livestock integration system (Santos et al., 2015), they promote soil structuring due to their abundant root system (Salton and Tomazi, 2014; Marchini et al., 2015).

Urochloa brizantha is a tropical perennial grass, with a stoloniferous, fasciculated, and fast-growing root system, adapted for clay to sandy loam textured soils, showing medium to low tolerance to drought and to lower fertility conditions, preferring soils with pH from 5 to 7.5 (Cook et al., 2012). *Urochloa humidicola* is also a perennial plant with large leaf matter and long creeping stolons; it is considered the most stoloniferous among the *Urochloas* and provides excellent coverage for soil protection (Lorenzi, 2000). In the past 15 years, the *Panicum* genus of grasses has also achieved great economic importance in Brazil (Macedo et al., 2013). *Panicum maximum* cv. Tanzania grass has high forage production, with rapid establishment and regrowth because of its root system, and can be used as a promoter of improvement in soil structural quality at deeper layers (Bogdan, 1977). These plants therefore have great potential for recovering areas degraded by mining.

The hypothesis is, due to their root system, perennial grasses are effective in the recovery of physical properties of soils degraded by mining. Therefore, the objective of this study was to quantify the root attributes of *Urochloa humidicola*, *Panicum maximum*, and *Urochloa brizantha* and relate them to the physical properties of a constructed minesoil in a coal mining area.

MATERIALS AND METHODS

Study area

The study was conducted in a field experiment in a coal mining area under concession of Riograndense Mining Company (*Companhia Riograndense de Mineração* - CRM), located in Candiota, RS, with geographical coordinates of 31° 33’ 56” S and 53° 43’ 30” W.

The main steps involved in (surface) strip mining of coal and subsequent topographic recomposition include: a) removal of the A, B, and/or C horizons of the original soil, which are transported by truck to cover the topographically leveled overburden piles; b) removal of overburden rocks through a high-capacity excavator (dragline); c) extraction of coal seams; d) deposition of the overburden rocks to fill the previous stripped area, which produces cone shaped piles that are leveled by bulldozers for topographic recomposition; and e) deposition of topsoil (natural soil A and/or B horizons removed in step a) to finish topographic restoration of the area, thus creating the “constructed” minesoil.

It is important to note that the coal is not processed in the *Candiota* Mine but is burned directly in its raw condition. Therefore, there is no generation of waste piles; contamination by pyrite in the constructed minesoil comes from pyrite-bearing rocks (sandstone and carboniferous shales) and unused low rank coal seams that are present in the overburden.

The soil in the study area was constructed in early 2003. A topsoil layer with average thickness of 0.40 m was placed on the overburden, with predominance of *Argissolo Vermelho Eutrófico típico* (Santos et al., 2013), a Rodic Lixisol (WRB, 2014) in a B horizon with a clay textural class (Table 1).

Before setting up the experiment, the soil was chiseled with a bulldozer to a depth of approximately 0.15 m, because of severe compaction caused by intense movement of machinery (trucks loaded with about 20 Mg of topsoil and Caterpillar model D8T bulldozers with 38 Mg weight, 259 kW gross power, length and width of track on the ground of 3.20 and 0.56 m per shoe, respectively, and ground contact area of 3.6 m^2). Afterwards, the area received dolomitic limestone equivalent to 10.4 Mg ha^{-1} effective calcium carbonate rating and 900 kg ha^{-1} NPK 5-20-20 fertilizer, based on results obtained from soil analysis.

The experiment was set up between September/October 2007 in 20 m^2 plots in a randomized block design with four replications. The species analyzed in this study were *Urochloa humidicola*, *Panicum maximum*, and *Urochloa brizantha*. In order to evaluate the changes resulting from the soil construction and the approximate time of recovery of soil properties, a natural soil under native vegetation was used as reference, located near the excavated strip at the time (in 2010), whose properties were determined in a previous study by Reis et al. (2014).

Table 1. Soil particle size in the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m soil layers after 58 months of revegetation

Layer	Sand	Silt	Clay	Textural class
m		g kg^{-1}		
0.00-0.10	336	211	453	Clayey
0.10-0.20	318	204	478	Clayey
0.20-0.30	259	274	467	Clayey

Sand, silt, and clay: pipette method.

Soil sampling and physical and chemical analysis

In July 2012 (about 5 years after experiment installation), 36 disturbed topsoil samples were collected in the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m soil layers (four blocks × three treatments × one replication per plot × three layers) for determination of the distribution of water-stable aggregates expressed in different size classes and the mean weight diameter of water-stable aggregates (MWD), as well as for determination of soil chemical properties and organic carbon (OC) content. For the water-stable aggregates, part of the soil samples were placed on a wooden tray and air dried at room temperature in the shade until the moisture reached the friability point, at which time the soil was manually broken along the natural planes of weakness to obtain the natural aggregates, passed in a sieve with mesh size of 9.52 mm, and then air dried for two weeks. The other part, for chemical characterization, was air dried, ground, and passed in a sieve with mesh size of 2.00 mm.

The sample for water-stable aggregates was divided into four subsamples of about 50 g each, one was used to determine soil moisture content, and the other three were wet sieved, following the method described by Kemper and Rosenau (1986), adapted by Palmeira et al. (1999). The intervals of the aggregate classes were C1: 4.76-9.52 mm, C2: 2.00-4.76 mm, C3: 1.00-2.00 mm, C4: 0.25-1.00 mm, C5: 0.105-1.00 mm, and C6: <0.105 mm. From these, the aggregates were separated into macroaggregates (>0.25 mm) and microaggregates (<0.25 mm), according to Tisdall and Oades (1982).

For chemical characterization and OC content, the following properties were determined: pH in water at the ratio of 1:1 (soil:water); Ca^{2+}, Mg^{2+}, and Al^{3+} extracted by 1 mol L^{-1} KCl and determined by atomic absorption spectrophotometer (Ca and Mg) and by titration with NaOH (Al); available K content was measured by the Mehlich-1 method and analyzed by flame photometry; and potential acidity (H+Al) as extracted by calcium acetate and determined by titration with NaOH. Based on the results of analysis, cation exchange capacity (CEC), base saturation (V), and aluminum saturation (m) were calculated according to Donagema et al. (2011). Organic carbon (OC) was determined by the Walkley-Black combustion method according to Tedesco et al. (1995).

Undisturbed topsoil samples (72) were collected in the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m layers (four blocks × three treatments × two replications per plot × three layers) with stainless steel cylinders (0.050 m height and 0.047 m diameter) for determination of soil bulk density and porosity, according to Donagema et al. (2011).

Through the equation BDcRest = 1.86 - 0.00071 clay, developed by Reichert et al. (2009), the bulk density of the soil restrictive for root growth for the different layers under study was estimated.

Root sampling

Root sampling was performed in July 2012 by the monolith method (Böhm, 1979), using a nail-board (0.40 m length × 0.30 m height × 0.035 m wide), for a total of 12 nail-boards (four replicates per treatment).

After collection, the monoliths were packed with plastic film and brought to the laboratory for washing and the root separation procedure. Washing consisted of soaking the plate for 24 h in 0.2 mol L^{-1} NaOH solution for soil dispersion and to facilitate cleaning the roots via running water or soft water jets to remove soil from the board. After the washing process, the roots along the board were separated by layers (from 0.00-0.10, 0.10-0.20, and 0.20-0.30 m), cut, and washed on a 1 mm sieve, stored in plastic bags, and refrigerated to a temperature of 2 °C. Subsequently, the roots were scanned on a HP Scanjet 3570C scanner for determination of root volume, length, area, and diameter through the SAFIRA Software. After scanning, the roots were dried at 65 °C for a period of 72 h to obtain dry root matter. The root density of each layer was calculated by the ratio of root dry matter to the soil volume.

Statistical data analysis

The data were analyzed to verify normal distribution and normality assumption of data using the Kolmogorov-Smirnov test. As the assumptions were met, the data were subjected to analysis of variance by the F test at a significance level of 5 %. When the treatment effect was significant, means were compared by the Tukey test ($p<0.05$). Statistical analyses were performed for each soil layer independently by means of Sigmaplot software (Sigmaplot, 2004).

Considering that the reference soil (natural soil under native vegetation) was not part of the experimental design, this treatment was not included in the statistical analysis.

RESULTS AND DISCUSSION

Chemical characterization of the constructed minesoil revegetated by grasses (Table 2) shows the effect of liming and fertilization in 2003, mainly in the 0.00-0.10 m layer. According to CQFSRS/SC (2004), the pH is above the reference value for summer perennial grasses (pH>5.5), the Ca^{2+} and Mg^{2+} contents are high (>4.0 $cmol_c\ kg^{-1}$ and >1.0 $cmol_c\ kg^{-1}$, respectively), K content is high (61-120 mg kg^{-1}) to very high (>120 mg kg^{-1}), base saturation is high (V >80 %), and Al saturation is very low (m <1%) to low (1-10 %) in the 0.00-0.10 m layer. In the 0.10-0.20 m soil layer, pH is close to the reference value, the Ca and Mg levels are high, the K content is average (41-60 mg kg^{-1}) to high (61-120 mg kg^{-1}), base saturation is low (45-64 %) to medium (65-80 %), and aluminum saturation is average (10.1 to 20 %) to high (>20 %). However, the chemical condition in the 0.20-0.30 m soil layer (low pH, low base saturation, and high Al saturation) indicates that not only did the incorporation of lime not reach this layer but that there is also the possible occurrence of acid mine drainage in a few replications of the collected monoliths, which reached the overburden layer (Table 3).

In general, the chemical conditions of the constructed minesoil are adequate for root growth to a depth of 0.20 m (Table 2); however, all the evaluated grasses showed reductions in their root attributes below the 0.00-0.10 m layer (Table 4).

Rooting depth is an important indicator of soil quality (Libardi and Jong van Lier, 1999) and the global average of rooting of grasses is 44 % root mass concentrated in the

Table 2. Chemical characterization of the constructed minesoil revegetated with grasses in the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m layers, after 58 months

Treatment	pH(H_2O)	Ca^{2+}	Mg^{2+}	H+Al	CEC	K	V	m
		$cmol_c\ kg^{-1}$				mg kg^{-1}	%	
				0.00-0.10 m				
U. humidicola	6.1^{ns}	5.1^{ns}	3.2^{ns}	2.0^{ns}	10.8^{ns}	199^{ns}	80^{ns}	0^{ns}
P. maximum	6.4^{ns}	6.0^{ns}	3.2^{ns}	1.7^{ns}	11.3^{ns}	119^{ns}	84^{ns}	1^{ns}
U. brizantha	6.6^{ns}	5.8^{ns}	3.3^{ns}	1.2^{ns}	10.7^{ns}	149^{ns}	89^{ns}	0^{ns}
				0.10-0.20 m				
U. humidicola	4.6^{ns}	4.1^{ns}	2.4^{ns}	4.2^{ns}	11.0^{ns}	83^{ns}	63^{ns}	16^{ns}
P. maximum	5.7^{ns}	4.0^{ns}	2.4^{ns}	5.2^{ns}	11.8^{ns}	53^{ns}	60^{ns}	25^{ns}
U. brizantha	4.8^{ns}	4.0^{ns}	2.7^{ns}	3.4^{ns}	10.3^{ns}	44^{ns}	67^{ns}	11^{ns}
				0.20-0.30 m				
U. humidicola	4.1^{ns}	2.8^{ns}	2.1^{ns}	7.3^{ns}	12.4^{ns}	37^{ns}	48^{ns}	34^{ns}
P. maximum	4.4^{ns}	2.4^{ns}	1.7^{ns}	8.8^{ns}	13.1^{ns}	30^{ns}	35^{ns}	53^{ns}
U. brizantha	3.6^{ns}	3.0^{ns}	2.2^{ns}	7.9^{ns}	13.3^{ns}	49^{ns}	42^{ns}	35^{ns}

pH in water (1:1); Ca and Mg: 1 mol L^{-1} KCl; H+Al: potential acidity, extracted with 0.5 mol L^{-1} $Ca(OAc)_2$ at pH 7.0; CEC: cation exchange capacity; K: extracted by Mehlich-1; V: base saturation; m: aluminum saturation. ^{ns}: not significant.

0-00-0.10 m layer and 75 % in the 0.00-0.30 m layer (Jackson et al., 1996; Peek et al., 2005). In the present study, the root mass (RM) concentration ranged from 66 to 81 % in the 0.00-0.10 m layer, decreasing to 13-28 % in the 0.10-0.20 m layer, and from 6 to 10 % in the 0.20-0.30 m layer, after 58 months of revegetation (Table 4). Therefore, the values of root growth observed in the constructed minesoil under study are not simply expressing a feature of the roots of most grasses, but are indicating the inadequate physical conditions below the 0.00-0.10 m layer, as shown by the values of macroporosity (Ma) (<0.10 $m^3 m^{-3}$) and bulk density (BD) (>1.40 Mg m^{-3}) (Table 5), considered restrictive to root development for most crops in clay soils (Reichert et al., 2003; Girardelo et al., 2011; Baquero et al., 2012).

In compacted soils, soil BD increases and Ma decreases (Reichert et al., 2007), directly influencing root growth (Silva et al., 2014). In this study, the presence of a compacted layer, and its consequent influence on reducing the root growth of the species, is apparent when analyzing the restrictive density to the roots (BDcRest) in the different layers of the constructed minesoil (Table 6).

The soil BD exhibited by the different treatments of species ranged from 1.28 to 1.37 Mg m^{-3} in the 0.00-0.10 m layer (Table 5), thus less than BDcRest (Table 6) calculated by the Reichert et al. (2009) equation. In contrast, in the 0.10-0.20 and 0.20-0.30 m layers, the BDcRest were equal to or lower than the BD exhibited by the soil in the different treatments after 58 months of revegetation, except for the *U. brizantha* treatment, which exhibited BD of 1.52 Mg m^{-3} in the 0.10-0.20 m layer and 1.42 Mg m^{-3} in the 0.20-0.30 m layer (Table 5).

Table 3. Thickness of the topsoil layer and presence of overburden in the different blocks and treatments to a soil depth of 0.30 m

Soil	Block	*U. humidicola*	*P. maximum*	*U. brizantha*
Topsoil	I	0.20 m	0.26 m	0.30 m
Overburden		0.10 m	0.04 m	absent
Topsoil	II	0.24 m	0.24 m	0.20 m
Overburden		0.06 m	0.06 m	0.10 m
Topsoil	III	0.30 m	0.30 m	0.30 m
Overburden		absent	absent	absent
Topsoil	IV	0.24 m	0.25 m	0.04 m
Overburden		0.06 m	0.05 m	0.26 m

Table 4. Root density (RD), root volume (RV), root length (RL), and mean root diameter (MRD) of the three grasses in the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m layers of the constructed minesoil after 58 months of the experiment

Treatment	RD	RV	RL	MRD
	kg m^{-3}	$m^3 m^{-3}$	m m^{-3}	mm
		0.00-0.10 m		
U. humidicola	5.96 ± 1.80 b	0.018 ± 0.006 ab	56.511 ± 26.345^{ns}	0.30 ± 0.02 ab
P. maximum	3.89 ± 2.23 b	0.009 ± 0.006 b	41.622 ± 18.791^{ns}	0.29 ± 0.01 b
U. brizantha	10.43 ± 1.87 a	0.025 ± 0.003 a	43.451 ± 8.277^{ns}	0.34 ± 0.02 a
		0.10-0.20 m		
U. humidicola	2.56 ± 0.85^{ns}	0.009 ± 0.004 a	23.463 ± 8.813 a	0.31 ± 0.01 ab
P. maximum	1.39 ± 0.13^{ns}	0.003 ± 0.001 b	18.329 ± 3.102 ab	0.29 ± 0.01 b
U. brizantha	1.73 ± 0.84^{ns}	0.004 ± 0.001 b	8.357 ± 1.044 b	0.35 ± 0.02 a
		0.20-0.30 m		
U. humidicola	0.51 ± 0.27^{ns}	0.002 ± 0.001^{ns}	5.750 ± 1.807^{ns}	0.32 ± 0.02^{ns}
P. maximum	0.57 ± 0.22^{ns}	0.001 ± 0.001^{ns}	9.523 ± 8.745^{ns}	0.29 ± 0.01^{ns}
U. brizantha	0.75 ± 0.36^{ns}	0.002 ± 0.001^{ns}	5.424 ± 2.746^{ns}	0.38 ± 0.10^{ns}

Values followed by the same lowercase letters in the column are not significantly different by the Tukey test ($p<0.05$). ^{ns}: not significant.

Table 5. Macro- and microaggregates, soil bulk density (BD), macroporosity (Ma), and organic carbon (OC) in the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m layers of the constructed minesoil 58 months after revegetation, and their differences in comparison to the reference soil (natural soil under native vegetation)

Treatment	Macroaggregate	Microaggregate	BD	Ma	OC
	%		Mg m^{-3}	m^{3} m^{-3}	g kg^{-1}
			0.00-0.10 m		
U. humidicola	90.1 ± 6.61 a	9.3 ± 6.61 b	1.35 ± 0.09^{ns}	0.13 ± 0.04^{ns}	7.9 ± 1.19 b
Δref (%)	1.73	-14.19	12.5	5.00	-60.48
P. maximum	90.4 ± 3.73 a	9.6 ± 3.73 b	1.37 ± 0.14^{ns}	0.12 ± 0.04^{ns}	8.1 ± 2.10 b
Δref (%)	1.45	-11.89	14.17	2.50	-59.48
U. brizantha	82.3 ± 2.48 b	17.7 ± 2.48 a	1.28 ± 0.07^{ns}	0.11 ± 0.05^{ns}	11.1 ± 1.91 a
Δref (%)	-7.64	62.76	6.67	-4.17	-44.81
Reference soil$^{(1)}$	89.1	10.8	1.20	0.12	20.0
	0.10-0.20 m				
H. humidicola	91.6 ± 2.51^{ns}	8.4 ± 2.51^{ns}	1.54 ± 0.12^{ns}	0.07 ± 0.04^{ns}	5.1 ± 1.78^{ns}
Δref (%)	13.59	-56.64	30.51	-42.05	-50.49
P. maximum	95.6 ± 1.97^{ns}	4.4 ± 1.97^{ns}	1.55 ± 0.09^{ns}	0.05 ± 0.03^{ns}	4.8 ± 0.83^{ns}
Δref (%)	18.56	-77.36	31.36	-54.20	-53.61
U. brizantha	88.1 ± 11.01^{ns}	11.9 ± 11.01^{ns}	1.52 ± 0.10^{ns}	0.05 ± 0.02^{ns}	7.2 ± 4.93^{ns}
Δref (%)	9.19	-38.29	28.81	-60.00	-30.02
Reference soil$^{(1)}$	80.6	19.3	1.18	0.12	10.3
	0.20-0.30 m				
H. humidicola	94.7 ± 4.00^{ns}	5.3 ± 4.00^{ns}	1.54 ± 0.13^{ns}	0.04 ± 0.03^{ns}	6.4 ± 2.95^{ns}
P. maximum	93.4 ± 3.33^{ns}	6.6 ± 3.33^{ns}	1.58 ± 0.06^{ns}	0.03 ± 0.01^{ns}	6.1 ± 2.37^{ns}
U. brizantha	93.9 ± 4.22^{ns}	6.0 ± 4.22^{ns}	1.42 ± 0.14^{ns}	0.07 ± 0.05^{ns}	7.8 ± 5.35^{ns}

$^{(1)}$ Reference soil: natural soil under native vegetation (Reis et al., 2014); Δref: increase (+) or decrease (-) compared to the reference soil. Values followed by the same lowercase letters in the column are not significantly different by the Tukey test ($p<0.05$). ^{ns}: not significant.

Table 6. Estimated critical values of soil bulk density for root growth (BDc Rest) for the 0.00-0.10, 0.10-0.20, and 0.20-0.30 m layers of the constructed mine soil revegetated by grasses using the equation of Reichert et al. (2009)

Layer	*Urochloa humidicola*	*Panicum maximum*	*Urochloa brizantha*
m		Mg m^{-3}	
0.00-0.10	1.53	1.54	1.54
0.10-0.20	1.53	1.53	1.53
0.20-0.30	1.52	1.54	1.56

In addition to reduction of root growth in species, and higher soil BD and lower soil Ma, in general, a higher percentage of macroaggregates is observed in the 0.10-0.20 m layer than in the 0.00-0,10 m soil layer (Table 5). The highest percentage of macroaggregates refers to large, cohesive, and sharp-edged aggregates present in the 0.10-0.20 m layer, whereas aggregates in the 0.00-0.10 m layer were less cohesive and more round-shaped, as perceived by visual observation and manipulation of aggregates during sample preparation, corresponding to “anthropogenic” and “pedogenic” aggregates, respectively, according to Reichert et al. (2016).

Greater soil aggregate cohesion, due to agricultural mechanization, was observed by Silva and Mielniczuk (1998). In the constructed minesoil, the aggregation results are likely also derived from soil particle cohesion, due to intense machine traffic carried out in soil construction, as already discussed by Stumpf et al. (2014). This type of condition was also reported in minesoils by Sencindiver and Ammons (2000) and in agricultural soils by

Voorhees (1983), Carpenedo and Mielniczuk (1990), Topp et al. (1997), Bergamin et al. (2010), and Conte et al. (2011).The soil used in recomposition of the mined area can reach its final construction stage in varying degrees of disintegration and compaction (Akala and Lal, 2001), and the use of machines at soil moisture close to the plastic limit is the main factor that causes compaction, since water reduces cohesion and acts as a lubricant between soil particles, allowing sliding and packing of particles when the soil is subjected to some sort of pressure (Luciano et al., 2012).

For their part, lower BD and higher Ma, as well as the lower proportion of large cohesive aggregates observed in the 0.00-0.10 m layer, represent a beneficial outcome for the soil under study because they come from the more extensive root growth of the species in this layer (Table 4), breaking the cohesive aggregates and possibly assisting in the formation of crumby aggregates (of chemical and biological origin). Materechera et al. (1992) also observed a lower proportion of large aggregates in agricultural clay soils cultivated with *Lolium multiflorum* compared to *Triticum spp* and *Pisum sativum*, attributing this result to the greater root length of *Lolium multiflorum*. The root system of grasses can lead to the change of more compact aggregates into less compact aggregates (Portella et al., 2012) by breaking the aggregates and then reshaping them (Terpstra, 1990) or by stresses generated in the soil-root interface during water extraction, which cause cracks in the soil (Ball et al., 2005).

A high concentration of roots in a given soil layer also produces greater amounts of OC, influencing reduction in BD and increasing soil porosity (Baquero et al., 2012; Matias et al., 2012.). However, higher OC intake shown by *U. brizantha* in the 0.00-0.10 m soil layer (Table 5) might not be the predominant factor in the formation of smaller and less cohesive aggregates in this layer because the OC levels are still very low. Rather, the aggregation observed is probably due to the higher proportion of roots of this species (Table 4) and its greater physical performance in the surface layer of the constructed minesoil.

Reclamation of degraded areas does not necessarily mean restoring the soil to the previous natural conditions (Mukhopadhyay et al., 2013) and, in the case of areas impacted by coal mining, the recovery of soil physical properties tends to be slow, as shown by differences between treatments and the undisturbed natural soil (Reference Soil), especially in subsurface layers (Table 5). Even after 58 months of revegetation, it can be observed that the BD in the 0.00-0.10 m layer of the constructed soil is 7 to 14 % higher and the OC content is 45 to 60 % lower than in the reference soil surface layer.

Degradation of the physical properties of the constructed minesoil compared to the reference soil, especially in the subsurface (0.10-0.20 m) layer, becomes evident through the higher BD (29 to 31 %) and lower Ma (42-60 %) and OC content (30-50 %). In addition, the percentage of macroaggregates (formed by compressive action of machine traffic) was 9-18 % higher compared to the natural soil under native vegetation (Table 5). However, it is expected that an improvement in the physical properties of the constructed minesoil will occur over the years, as found by Wick and Daniels (2009), who observed aggregate distribution in a minesoil similar to the natural soil 16-20 years after surface coal mining.

In this regard, Reichert et al. (2016) made a thermodynamic approach to the development of the physical properties of an agricultural system 14 years after adoption of no-till, noting that withdrawal of the disruption caused by soil mobilization under conventional tillage would lead the system to a decrease in entropy production, with changes in the soil structure from initial “anthropogenic” aggregates, prismatic type, to “pedogenic” aggregates, which, ultimately, reaching a state of dynamic equilibrium, would become crumby due to biological action. Similarly, revegetation of the constructed minesoil and growth of its root system, with input of organic matter, restoring flows of matter and energy captured by photosynthesis, would lead the system to a similar situation, with declining entropy production and changes in the state of soil aggregation. Considering the extreme degree of disturbance caused by mining, however, a longer time can be expected to reach a steady state similar to the undisturbed system.

CONCLUSIONS

The results confirm the hypothesis that the grass root system recovers the physical properties of the 0.00-0.10 m layer of constructed minesoil after 58 months of revegetation.

The higher percentage of large aggregates, higher bulk density, and lower macroporosity below the 0.00-0.10 m soil layer indicates the presence of a degraded layer, negatively influencing grass root system development.

The *Urochloa brizantha* species showed the highest root mass in the surface layer, influencing the breakdown of large and cohesive aggregates and allowing their change into smaller crumby aggregates.

In the 0.10-0.20 m layer of the constructed minesoil, *Urochloa humidicola* exhibited the highest volume and root length; nevertheless, changes in soil physical properties were not observed, indicating that the revegetation time was not enough to provide improvements below the surface layer.

ACKNOWLEDGMENTS

Our thanks to the *Companhia Riograndense de Mineração* (CRM), CNPq - *RedeCarvão*, CAPES, and CNPq for logistical and/or financial support.

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