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Temporal dynamics of minesoil restoration in Southern Brazil: A two-decade monitoring of soil physical attributes and organic carbon content

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ABSTRACT

Brazil covers a huge territory (852 Mha) with biomes distributed from North to South of the country. In Southern Brazil, about 24% of the area covered by the Pampa Biome was lost between 1985 and 2022, mainly due to conversion to agriculture, but also due to coal mining. This region holds the largest coal mine in Latin America, namely Candiota Mine, which represents 38 % of the Brazilian coal reserves. Minesoils typically exhibit severe compaction and poor structure, jeopardizing its reclamation and reintegration to the biome. This study aimed to assess the temporal changes in physical attributes and total organic carbon (TOC) content of a minesoil as affected by perennial grasses in a long-term field randomized complete block design experiment located in the Candiota Mine region. Based on prior research indicating superior performance of *Urochloa brizantha* for amelioration of this minesoil, we hypothesized a continued outstanding performance of this grass over the others to enhance the structure and increase the TOC content of the minesoil. Experimental treatments (with four replicates) consisted of perennial grasses used for minesoil revegetation: *Hemarthria altissima*, *Paspalum notatum*, and *Urochloa brizantha*. Minesoil bulk density (Bd), macroporosity (Ma), total porosity (Tp), percentage of macroaggregates and microaggregates, and TOC content were evaluated in the different treatments at 0.00–0.10 and 0.10–0.20 m layers at four restoration time points (0.5, 8.6, 14.6 and 20 years). The elevated percentage of macroaggregates and Bd close to or > 1.50 Mg m^{-3} observed for the 0.00–0.10 and 0.10–0.20 m layers up to 8.6 years reflect the persistent compaction caused by the traffic of heavy machinery on the minesoil during landscape restoration. Minesoil compaction was remarkably attenuated after 14.6 years of restoration, likely due to root-induced disruption of aggregates formed by compression followed by soil re-aggregation. This was consistent with a reduction of Bd and an increase of Ma and TOC of the minesoil at this same restoration age. *Urochloa brizantha* was the pioneer grass alleviating minesoil compaction but this outstanding performance leveled off after 14.6 years compared to the other grasses, contracting our hypothesis. This was confirmed by the ordination of *Urochloa brizantha* close mainly to *Hemarthria altissima* in a principal component analysis biplot of the data set, indicating similar interrelations of the examined attributes after 20 years of restoration, regardless of the grass species.

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1. Introduction

Brazil covers an area of approximately 852 Mha and encompasses various biomes. About 33.2 % (282.5 Mha) of this territory is used for agriculture, mainly arable (61.0 Mha) and livestock (164.3 Mha) farming. From 1985 to 2022, the Cerrado and Pampa Biomes lost 25 and 24 %, respectively, of their coverage area, together totaling about 35 Mha of native vegetation loss, mainly due to the introduction of farming systems (MapBiomas, 2023a). In Brazill, the Pampa Biome is found exclusively in the southernmost state, namely Rio Grande do Sul (RS), and its vegetation consists of native grasslands, which cover 69 and 2.3 % of the RS and Brazilian land area, respectively. The Pampa extends to neighboring countries, Argentina and Uruguay, covering in total 75 Mha (MMA, 2024).

The average soil organic carbon (SOC) stock in the 0.00–0.30 m layer of the Pampa Biome is estimated at 50 Mg ha^{-1} (MapBiomas, 2023b), and anthropogenic changes leading to soil degradation and SOC loss as CO_2 to the atmosphere must be urgently monitored (Oliveira et al., 2017). In addition to farming systems, other anthropogenic activities in the Pampa, as open-pit coal mining, contribute to native vegetation suppression. The Candiota Mine in RS, Brazil, holds 38 % of the national coal reserves and it is the largest coal mine in Latin America (MME - Ministry of Mines and Energy, 2018). Open-pit coal mining involves the removal of vegetation and soil down to the profitable coal banks. Thereafter, the open pit is filled with residual rocks and overburden, followed by a layer of stand-by stored soil, which may vary in thickness and texture, depending on the availability of soil and mining practices. This reconfiguration of the landscape leads to critical compaction and depleted quality of the reconstructed soil (Stumpf et al., 2016; Duncan et al., 2020; Pinto et al., 2020; Couic et al., 2021; Fernandez et al., 2023; Miguel et al., 2023), also called minesoil (Guzman et al., 2019).

The high and persistent compaction of minesoils hinders their reclamation, as revegetation species must feature a vigorous root system to adapt to the inadequate physical conditions of newly formed minesoils. Perennial grasses are suitable candidates for revegetating minesoils in the Candiota Mine region, as they exhibit vigorous root system and because grasses predominate in the Pampa Biome (MapBiomas, 2023b). However, monitoring the performance of grass species in minesoils over time is essential for a better understanding of the restoration process of minesoils. In this context, Miguel et al. (2023) observed a progressive improvement of soil physical attributes at the 0.00−0.20 m layer of a Brazilian minesoil, between 4.8 and 10.6 years of minesoil revegetation with perennial grasses. This was assigned to root-induced decompaction of topsoil through disrupting compression-formed cohesive aggregates, thereby enhancing soil macroporosity and increasing SOC content. Similarly, Feng et al. (2021) reported significant correlations between grass root biomass, soil organic matter (SOM) content and soil aggregation in an 8-year revegetated minesoil in China. In line with this, Stumpf et al. (2016) evaluated root attributes of six perennial grasses grown for 8.6 years in a Candiota minesoil. The authors found that 62−68 %, 19−29 % and 6−18 % of the root mass was located at the 0.00−0.10, 0.10−0.20 and 0.20−0.30 m layer of the minesoil, respectively, and reported significant correlations of root density with soil bulk density (Bd), macroporosity (Ma), and SOC content at 0.20 m depth. Among the grasses, *Urochloa brizantha* exhibited the highest root density, volume and length, especially in the compacted layer below 0.10 m depth, evidencing the greater potential of this grass for improving the minesoil structure, at least at that revegetation age.

Chronological monitoring of minesoil properties is a recognized approach to identify outstanding revegetation techniques and/or species that can sustain long-term ecological restoration of minesoils (Li et al., 2018; Chen et al., 2020; Zhang et al., 2022). Several studies have documented the improvement of minesoil properties through revegetation with grasses (Kumar et al., 2018; Feng et al., 2021; Stutler et al., 2022). However, experimental monitoring of the temporal evolution of the physical properties of grass-revegetated minesoils, at field scale and with statistical control, is rare or unreported for Brazil, particularly for those minesoils located in the Pampa Biome.

To our knowledge, our field experiment installed in 2003 in the Candiota Mine is the only long-term study in Brazil designed with statistical rigor to monitor the progress of various minesoil properties as affected by grasses. The overall goal of the experiment is to identify outperforming grasses for the long-term reclamation of this minesoil. The specific objective of the present study was to investigate the temporal evolution of several physical properties and total organic carbon (TOC) content of the minesoil in two soil layers as affected by perennial grasses (*Hemarthria altissima*, *Cynodon dactylon*, *Urochloa brizantha*). Particularly, we aimed to improve our understanding of the dynamics of aggregate formation in this minesoil. We hypothesized that the perennial grasses used for the minesoil revegetation ameliorate the soil attributes progressively both at 0.00−0.10 and 0.10−0.20 m layer over four time points spanning 20 years of revegetation. In addition, based on our previous studies indicating superior performance of *Urochloa brizantha* for initial soil structure amelioration, we hypothesized a continued superior performance of this grass over the others.

2. Materials and methods

2.1. Experimental area history

The study was conducted in the Candiota Mine domain, RS State, Southern Brazil (Fig. 1), where the climate is subtropical humid (Cfa), the average annual air temperature is 17 °C and average annual rainfall is 1400 mm, including cold winter and hot summer (Alvares et al., 2013).

The experimental area was set up in November/December 2003 in a randomized complete block design with four replications (plots of 4 ×5 m, 20 m^2). Before grasses implantation, 84 samples of the topsoil were taken across the experimental area for TOC content and texture determination to ensure a proper disposal of the four experimental blocks. In the same occasion, the natural soil (unmined), a Rodic Lixisol (IUSS Working Group WRB, 2015) was sampled and characterized in the same way as a mixture of its horizons compose the topsoil of the formed minesoil. The horizons, clay content, TOC content and soil color of the natural soil and individual blocks of the experimental area are displayed in Table 1.

The topsoil of the four blocks of the experimental area exhibited a 2.5YR color, clay content from 448 to 455 g kg^{-1} and TOC between 4.9 and 5.6 g kg^{-1} , which are consistent with characteristics of the B horizon of the natural soil (Table 1). Therefore, it is inferred that the topsoil of the minesoil consists mostly of the B-horizon of the natural (premining) soil, which is typically placed over the overburden layer in this area. The four blocks were designed to capture the terrain's slope.

Before grasses implantation, the topsoil was chiseled with a bulldozer to a 0.15 m depth as it exhibited signs of severe compaction caused by the traffic of the heavy machinery used for topographic recomposition of the landscape. In this occasion, soil pH correction and fertilization were performed using dolomitic limestone (10.4 Mg ha^{-1}) and 900 kg ha^{-1} of a 5−20−20 fertilizer (45 kg N, 180 kg P2O5, and 180 kg K_2O), based on results of soil analysis. Annually, all plots of the experiment received 250 kg ha^{-1} of a 5−30−15 fertilizer (12.5 kg N, 75 kg P_2O_5, and 37.5 kg K_2O) and 250 kg ha^{-1} of urea.

Several grass and legume species were tested as monoculture or as consortiums, as described in Stumpf et al. (2016). In the present study, the results refer to monoculture of three perennial grasses of the Poaceae Family: *Hemarthria altissima* (Poir.) Stapf & C.E. Hubbard, *Paspalum notatum* Flüggé, cv. Pensacola, *Cynodon dactylon* (L.) Pers. cv. Tifton, and *Urochloa brizantha* (Hochst. ex A. Rich.) Stapf.

Annual precipitation records comprising the study period (2003–2023) were obtained from the meteorological station located in the Candiota Mine. These data are presented in Fig. 2 to support the

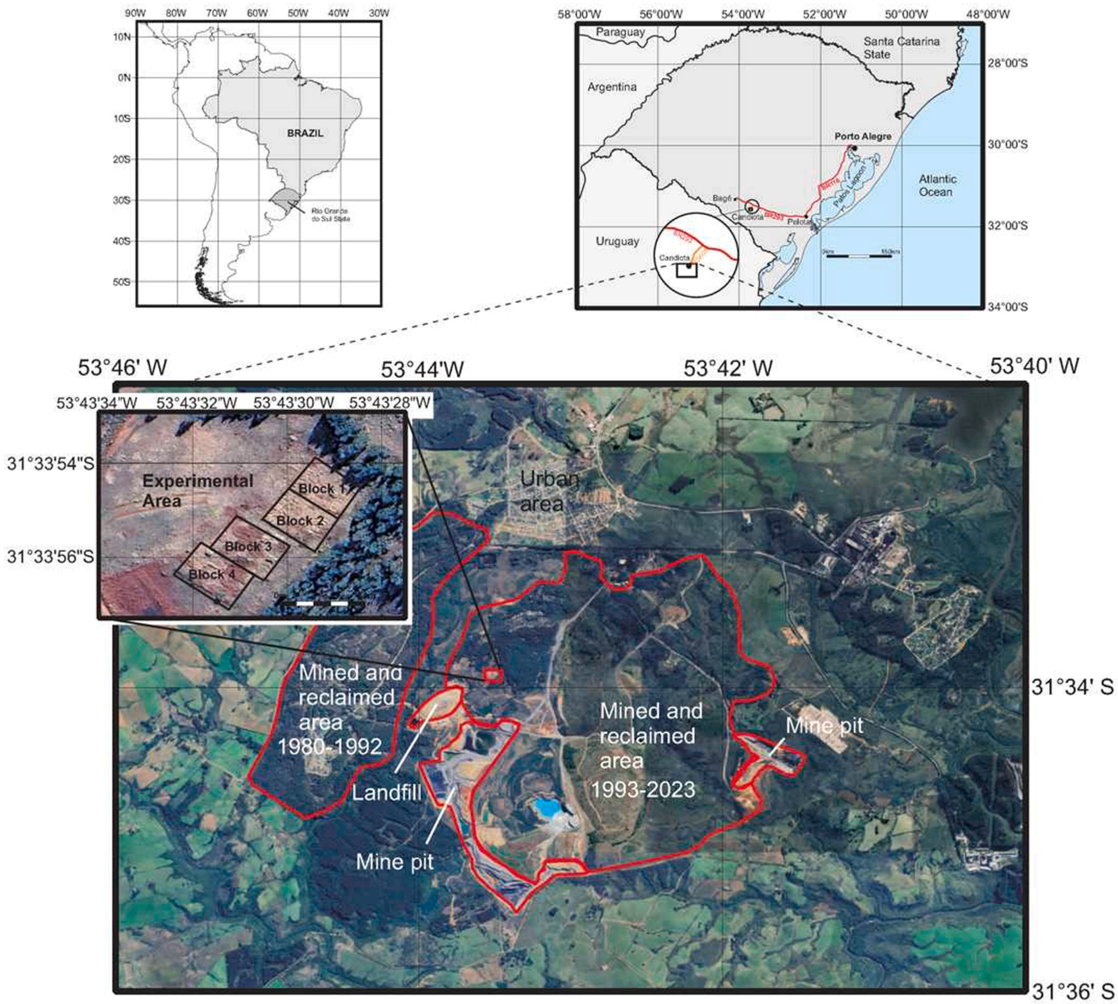

Fig. 1. Minesoil field experiment located in the Candiota coal Mine, Southern Brazil. Source: Miguel et al. (2023).

Table 1
Clay content, total organic carbon content, and color of the minesoil topsoil (0.00−0.20 m layer) in the four experimental blocks and of the horizons (Hz) of the natural soil (unmined soil located in the mining front) at start of the experiment.

Soil	Blocks or Horizons	Clay (g kg^{-1})	Organic carbon (g kg^{-1})	Color
Minesoil	Block 1	455	4.9	2YR
	Block 2	448	5.5	
	Block 3	450	4.4	
	Block 4	455	5.6	
Natural Soil	Hz A	231	11.0	5YR
	Hz AB	340	8.0	
	Hz BA	402	6.0	2YR
	Hz Bt1	550	5.0	
	Hz Bt2	470	3.0	
	Hz BC	445	3.0	

interpretation of the results related to soil restoration (Fig. 2)

2.2. Soil sampling and analyses

After 20 years of revegetation (October/November 2023), soil samples were collected at 0.00−0.10 and 0.10−0.20 m layers for analysis of Bd, Ma and total porosity (Tp), percentage of macroaggregates and microaggregates, and soil TOC content, as described below. This dataset was compared to that obtained when revegetation completed 0.5

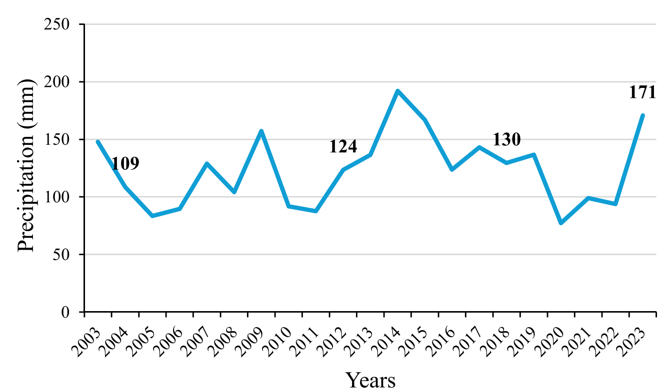

Fig. 2. Monthly average precipitation in every year since installation of experiment until the last soil sampling campaign (2003–2023) in the Candiota Mine region. Values in the plot area refer to precipitation in the years of soil sampling.

(Franco, 2006), 8.6 (Stumpf et al., 2016) and 14.6 years (Rodrigues, 2019).

In 2023, twenty-four soil blocks (3 grass species, 4 experimental blocks, 2 layers) were collected with a shovel blade to determine the TOC content and the distribution of water-stable aggregates in different size classes. These soil samples were air-dried at room temperature in the shade until the moisture reached the friability point. Thereafter, the soil was broken into large clods along their natural planes of weakness to obtain natural aggregates, sieved at 9.52 mm, and then air-dried for two weeks. From this sample, sub-samples were taken (50 g), and submitted to wet sieving with vertical oscillation following the method described by Kemper and Rosenau (1986) and adapted by Palmeira et al. (1999). The aggregates were divided into the following diameter classes: 9.52–4.76 mm; 4.76–2.0 mm; 2.00–1.00 mm; 1.00–0.25 mm; 0.25–0.105 mm, and < 0.105 mm. These data are presented as percentage of macroaggregates (> 0.25 mm) and microaggregates (< 0.25 mm) according to Tisdall and Oades (1982).

Soil Bd and Ma were determined according to Teixeira et al. (2017). For this, 96 undisturbed soil samples (3 grasses x 4 experimental blocks x 4 sampling points x 2 layers) were collected with stainless steel cylinders (0.05 m height and 0.047 m internal diameter, 86.7 cm^3). For Ma determination, the soil in the cylinder was saturated with water by capillary for 24 h and placed on a tension table for equilibration at 6 kPa to drain macropores (with diameter > 0.05 mm). The samples were weighed and the difference between the saturated and drained soil was considered the Ma. After drainage, the samples were dried at 105 °C to constant weight. The weight difference between the soil equilibrated at 6 kPa and the dried soil corresponded to microporosity (Mi). The sum of Ma and Mi corresponded to soil Tp. The soil Bd was determined by dividing the soil dry weight by the volume of the cylinder.

The soil TOC content was determined by the Walkley-Black combustion method in the fine earth fraction (< 2 mm) according to Teixeira et al. (2017) to comply with the soil fertilization and liming manual of the Brazilian Soil Science Society for the RS state where the experiment is located (CQFS, 2016).

2.3. Statistical analysis

Normal distribution of the data was tested using the Shapiro-Wilk test, and the homogeneity of variances was checked with Levene's test. Following the confirmation of data normal distribution and homogeneity of variances, the data were submitted to a two-way repeated-measures ANOVA (perennial grasses and restoration time as main factors). If significant differences were indicated by the ANOVA, the means of the variables were compared by Tukey's test. The statistical significance level is shown at $p < 0.10$, $p < 0.05$ and $p < 0.01$. Principal component analysis (PCA) was applied to the dataset to reveal shifts in the soil attributes and their interrelations induced by the perennial grasses over restoration time in each soil layer (0.00–0.10 and 0.10–0.20 m).

3. Results

In the 0.00–0.10 m layer, a significant interaction between the factors grass species and time of restoration was observed only for macro and microaggregates percentage ($p < 0.001$, Table 2). Both main factors (grass and time) significantly affected the soil Bd ($p = 0.038$ and $p = 0.064$, respectively), Ma ($p = 0.052$ and $p < 0.001$, respectively) and Tp ($p = 0.011$ and $p = 0.003$, respectively) (Table 2). The soil TOC content was significantly affected only by the time of restoration ($p < 0.001$, Table 2).

In the 0.10–0.20 m layer, a significant interaction between the factors grass species and time of restoration was observed for Bd ($p < 0.021$), microaggregates ($p = 0.074$), and macroaggregates ($p = 0.089$). Both factors (grass and time) significantly affected soil Tp ($p < 0.001$) and Ma ($p < 0.004$ and $p < 0.006$, respectively), whereas the time of restoration significantly affected the TOC content of the soil ($p = 0.001$) (Table 2).

3.1. Macroaggregates and microaggregates percentage

In the 0.00–0.10 m layer, the macroaggregates percentage after 0.5 years of restoration was statistically higher in *Cynodon dactylon* (90.8 %) compared to *Hemarthria altissima* (88.0 %), whereas *Urochloa brizantha* did not differ from these treatments (Table 3). After 8.6 years of restoration, the percentage of macroaggregates was lower in *Urochloa brizantha* (84.1 %) than in *Cynodon dactylon* (92.2 %) and *Hemarthria altissima* (91.0 %), which did not differ statistically from each other (Table 3). After 14.6 years of restoration, the macroaggregatespercentage decreased remarkably compared to the previous years, ranging from 43.4 % to 44.1 %, without statistical differences between the grasses (Table 3). This was followed by an outstanding re-increase of macroaggregates (%) at 20 years of restoration, when the macroaggregates in *Cynodon dactylon* (85.9 %) and *Urochloa brizantha* (84.4 %) did not differ from each other but were significantly higher compared to *Hemarthria altissima* (78.1 %) (Table 3).

The microaggregates percentage in the 0.00–0.10 m layer over the years of restoration across treatments followed an inverse trend compared to the macroaggregates percentage. The microaggregates percentage after 0.5 years of restoration varied from 9.7 % to 12.0 %, without statistical differences between treatments (Table 3). After 8.6 years of restoration, the microaggregates percentage was significantly higher in *Urochloa brizantha* (15.9 %) compared to *Hemarthria altissima* (9.0 %) and *Cynodon dactylon* (7.8 %), which were not statistically different from each other (Table 3). This was followed by a remarkable increase in the microaggregates percentage after 14.6 years of restoration, when it ranged from 55.8 % to 56.6 % without significant differences between grass species (Table 3). The microaggregates percentage notably decreased after 20 years of restoration to 21.9 % in *Hemarthria altissima*, which was statistically higher than that in *Urochloa brizantha* (15.6 %) and *Cynodon dactylon* (14.1 %) (Table 3).

In the 0.10–0.20 m layer, the macroaggregates percentage after 8.6 years of restoration remained between 88.9 % and 96.0 %, without statistical differences between grasses, neither after 0.5 nor after 8.6 years of restoration (Table 4). A similar macroaggregates percentage between grass species was observed after 14.6 years but was clearly lower (42.2–43.6 %) compared to the previous years (Table 4). Only after 20 years of restoration, the macroaggregates percentage differed significantly between grass species, with the lowest macroaggregate (%) found in *Hemarthria altissima* treatment (75.3 %) compared to *Cynodon dactylon* (81.1 %) and *Urochloa brizantha* (83.9 %), which did not differ statistically from each other (Table 4).

The microaggregate percentage in the 0.10–0.20 m layer exhibited a reverse pattern to that of macroaggregate percentage over the years of restoration and across treatments. After the first 8.6 years of restoration,

Table 2
Two-way ANOVA p values for the main factors grass species (Grass) and time of restoration (Time) and their interaction (Grass*Time) for the different physical attributes and total organic carbon content of the soil evaluated at 0.00–0.10 m and 0.10–0.20 m layer. All p values < 0.10 are highlighted with bold writing and were considered significant for discussion.

Soil attributes	Grass	Time	Grass*Time
0.00–0.10 m			
Macroaggregates	**0.008****	**< 0.001*****	**< 0.001*****
Microaggregates	**0.076***	**< 0.001*****	**< 0.001*****
Bulk density	**0.038****	**0.064***	0.861
Macroporosity	**0.052***	**< 0.001*****	0.586
Total porosity	**0.011****	**0.003****	0.635
Total organic carbon	0.367	**< 0.001*****	0.906
0.10–0.20 m			
Macroaggregates	0.378	**< 0.001*****	**0.089***
Microaggregates	0.52	**< 0.001*****	**0.074***
Bulk density	**0.013****	**< 0.001*****	**0.021****
Macroporosity	**0.004****	**0.006****	0.667
Total porosity	**< 0.001*****	**< 0.001*****	0.518
Total organic carbon	0.585	**0.001****	0.389

* $p < 0.10$;
** $p < 0.05$;
*** $p < 0.001$

Table 3
Minesoil physical attributes and total organic carbon content at 0.5, 8.6, 14.6 and 20 years of restoration with perennial grasses in the 0.00–0.10 m layer.

Grass	Restoration (years)				Grass average (over years)
	0.5	8.6	14.6	20	
	Macroaggregates (%)				
Urochloa brizantha	89.38 ± 3.89 ab***	84.07 ± 3.90 b	44.07 ± 1.02 ns	84.40 ± 3.18 a	75.48
Hemarthria altissima	88.00 ± 1.44 b	90.96 ± 1.32 a	44.19 ± 0.56	78.12 ± 2.93 b	75.32
Cynodon dactylon	90.80 ± 4.03 a	92.21 ± 2.96 a	43.41 ± 1.31	85.90 ± 3.10 a	78.08
Grass group average	89.39	89.08	43.89	82.81	
	Microaggregates (%)				
Urochloa brizantha	10.62 ± 3.88 ns	15.93 ± 3.90 a***	55.93 ± 1.02 ns	15.60 ± 3.18 b	24.52
Hemarthria altissima	11.99 ± 1.42	9.04 ± 1.32 b	55.81 ± 0.56	21.88 ± 2.93 a	24.68
Cynodon dactylon	9.65 ± 4.46	7.79 ± 2.96 b	56.60 ± 1.31	14.10 ± 3.10 b	22.03
Grass group average	10.75	10.92	56.11	17.19	
	Bulk density (Mg m^{-3})				
Urochloa brizantha	1.40 ± 0.03 ns	1.22 ± 0.21 ns	1.32 ± 0.08 ns	1.27 ± 0.22 ns	1.31 B**
Hemarthria altissima	1.47 ± 0.04	1.40 ± 0.07	1.38 ± 0.04	1.31 ± 0.07	1.39 A
Cynodon dactylon	1.45 ± 0.08	1.30 ± 0.05	1.39 ± 0.09	1.37 ± 0.12	1.38 AB
Grass group average	1.44 A*	1.31 B	1.37 AB	1.32 B	
	Macroporosity (m^3 m^{-3})				
Urochloa brizantha	0.03 ± 0.02 ns	0.15 ± 0.09 ns	0.16 ± 0.02 ns	0.15 ± 0.02 ns	0.12 A*
Hemarthria altissima	0.03 ± 0.01	0.09 ± 0.05	0.15 ± 0.01	0.10 ± 0.02	0.09 B
Cynodon dactylon	0.03 ± 0.01	0.15 ± 0.03	0.13 ± 0.04	0.12 ± 0.03	0.11 AB
Grass group average	0.03 B***	0.13 A	0.15 A	0.12 A	
	Total porosity (m^3 m^{-3})				
Urochloa brizantha	0.48 ± 0.04 ns	0.49 ± 0.06 ns	0.52 ± 0.03 ns	0.57 ± 0.04 ns	0.51 A**
Hemarthria altissima	0.44 ± 0.03	0.42 ± 0,04	0.50 ± 0.03	0.50 ± 0.03	0.46 B
Cynodon dactylon	0.45 ± 0.04	0.47 ± 0.02	0.48 ± 0.02	0.50 ± 0.05	0.47 B
Grass group average	0.45 B**	0.46 B	0.50 A	0.52 A	
	Total organic carbon (g kg^{-1})				
Urochloa brizantha	5.48 ± 0.37 ns	10.37 ± 2.71 ns	24.03 ± 6.47 ns	24.28 ± 7.40 ns	16.04 ns
Hemarthria altissima	5.22 ± 0.46	8.40 ± 1.53	24.17 ± 8.08	21.09 ± 5.26	14.72
Cynodon dactylon	5.20 ± 0.45	8.37 ± 1.97	21.16 ± 7.72	20.09 ± 4.54	16.71
Grass group average	5.30 B***	9.04 B	23.12 A	21.82 A	

Means of grass species treatments followed by different lowercase letter within a column (time of restoration) differ statistically according to Tukey's test. Means at specific restoration times regardless of grass species (grass group average) and mean of a grass type regardless of restoration years (grass average) followed by different uppercase letter differ statistically according to Tukey's test. ns: not significant; *$p < 0.10$; **$p < 0.05$; ***$p < 0.001$.

the microaggregate percentage ranged from 4.0 % to 9.8 %, without statistical differences between grass species, neither after 0.5 nor after 8.6 years of restoration (Table 4). The similar microaggregate percentage between the treatments was also observed after 14.6 years of restoration, but with consistently higher values (56.4–57.8 %) compared to the previous years (Table 4). After 20 years of restoration, a higher microaggregate percentage was observed in *Hemarthria altissima* (24.7 %) compared to *Urochloa brizantha* (16.1 %) and *Cynodon dactylon* (18.9 %) treatment, which did not differ from each other (Table 4).

3.2. Bulk density, macroporosity and total porosity

In the 0.00–0.10 m layer, the grasses average of soil Bd after 0.5 years of restoration (1.44 Mg m^{-3}) significantly decreased to 1.31 Mg m^{-3} at 8.6 years, but without further significant change after 14.6 years (1.37 Mg m^{-3}) and 20 years of restoration (1.32 Mg m^{-3}) (Table 3). The average soil Bd in the grass species treatments (regardless of restoration years) was higher in *Hermathria altissima* (1.39 Mg m^{-3}) than in *Urochloa brizantha* (1.31 Mg m^{-3}), whereas the soil Bd in *Cynodon dactylon* treatment (1.38 Mg m^{-3}) did not differ significantly from these values (Table 3). In the 0.10–0.20 m layer, the soil Bd in the three grass species treatments after 0.5 years was 1.67 Mg m^{-3} (Table 4). After 8.6 years of restoration, the Bd in *Cynodon dactylon* (1.59 Mg m^{-3}) and *Hemarthria altissima* treatment (1.57 Mg m^{-3}) did not differ statistically from each other but were significantly higher than that in *Urochloa brizantha* (1.37 Mg m^{-3}) (Table 4). After 14.6 years of restoration, the highest Bd was observed in *Cynodon dactylon* (1.54 Mg m^{-3}) and the lowest in *Hemarthria altissima* treatment (1.39 Mg m^{-3}), whereas the Bd in *Urochloa brizantha* (1.44 Mg m^{-3}) did not differ from these two values (Table 4). After 20 years of restoration, *Cynodon dactylon* treatment persistently exhibited the highest Bd (1.59 Mg m^{-3}), which was statistically higher than that found in *Hemarthria altissima* (1.46 Mg m^{-3}) and *Urochloa brizantha* (1.38 Mg m^{-3}) treatment, which were statistically comparable (Table 4).

In the 0.00–0.10 m layer, the grass species group average (regardless of grass species) of Ma after 0.5 years (0.03 m^3 m^{-3}) significantly increased to 0.13 m^3 m^{-3} after 8.6 years of restoration, but without further significant changes after 14.6 (0.15 m^3 m^{-3}) and 20 years (0.12 m^3 m^{-3}) of restoration (Table 3). The grass average (regardless of restoration age) of Ma for *Urochloa brizantha* (0.12 m^3 m^{-3}) was slightly, but significantly higher than that for *Hemarthria altissima* treatment (0.09 m^3 m^{-3}), whereas the Ma observed for *Cynodon dactylon* (0.11 m^3 m^{-3}) was statistically equivalent to these two averages (Table 3). In the 0.10–0.20 m layer, the grass group average (regardless of grass type) of Ma at 0.5 years (0.07 m^3 m^{-3}) did not differ statistically from that observed at 8.6 (0.07 m^3 m^{-3}) and 20 years (0.07 m^3 m^{-3}) of restoration, and only a transient significant increase of 86 % of Ma was observed at 14.6 years (0.13 m^3 m^{-3}) of restoration (Table 4). The grass average (regardless of restoration age) of Ma for *Urochloa brizantha* treatment (0.12 m^3 m^{-3}) was statistically higher by 50 and 100 % compared to that observed for *Hemarthria altissima* (0.08 m^3 m^{-3}) and *Cynodon dactylon* (0.06 m^3 m^{-3}), respectively, which did not differ statistically from each other (Table 4).

In the 0.00–0.10 m layer, the grass species group average (regardless of grass species) of soil Tp after 0.5 years (0.45 m^3 m^{-3}) remained statistically unaltered after 8.6 years of restoration (0.46 m^3 m^{-3}), increased statistically to 0.50 m^3 m^{-3} after 14.6 years but not further after 20 years of restoration (0.52 m^3 m^{-3}) (Table 3). The grass average (regardless of restoration age) for soil Tp was 9–11 % higher in *Urochloa brizantha* (0.51 m^3 m^{-3}) than in *Hemarthria altissima* (0.46 m^3 m^{-3}) and *Cynodon dactylon* treatment (0.47 m^3 m^{-3}), which did not differ significantly from each other (Table 3). In the 0.10–0.20 m layer, the grass species group average (regardless of grass species) of soil Tp after 0.5 years (0.42 m^3 m^{-3}) and 8.6 years (0.40 m^3 m^{-3}) did not differ

Table 4
Minesoil physical attributes and total organic carbon content at 0.5, 8.6, 14.6 and 20 years of restoration with perennial grasses in the 0.10–0.20 m layer.

Grass	Restoration (years)				Grass average (over years)
	0.5	8.6	14.6	20	
	Macroaggregates (%)				
Urochloa brizantha	91.25 ± 6.32 ^{ns}	93.58 ± 3.4 ^{ns}	43.56 ± 0.99 ^{ns}	83.93 ± 3.71 a*	78.08
Hemarthria altissima	88.86 ± 5.34	96.01 ± 0.27	43.29 ± 0.70	75.34 ± 2.66 b	75.88
Cynodon dactylon	90.95 ± 1.98	95.52 ± 2.40	42.20 ± 3.15	81.10 ± 4.94 a	77.44
Grass group average	90.36	95.04	43.02	80.12	
	Microaggregates (%)				
Urochloa brizantha	8.75 ± 6.32 ^{ns}	6.42 ± 3.43 ^{ns}	56.44 ± 0.99 ^{ns}	16.07 ± 3.71 b*	21.92
Hemarthria altissima	9.82 ± 6.23	3.99 ± 0.37	56.71 ± 0.70	24.66 ± 2.66 a	23.79
Cynodon dactylon	9.05 ± 1.98	4.48 ± 2.40	57.80 ± 3.15	18.91 ± 4.94 b	22.56
Grass group average	9.21	4.97	56.98	19.88	
	Bulk density (Mg m^{-3})				
Urochloa brizantha	1.67 ± 0.06 ^{ns}	1.37 ± 0.20 b**	1.44 ± 0.08 ab	1.38 ± 0.03 b	1.46
Hemarthria altissima	1.67 ± 0.05	1.57 ± 0.05 a	1.39 ± 0.08 b	1.46 ± 0.04 b	1.52
Cynodon dactylon	1.67 ± 0.06	1.59 ± 0.04 a	1.54 ± 0.02 a	1.59 ± 0.04 a	1.60
Grass group average	1.67	1.51	1.46	1.48	
	Macroporosity (m^3 m^{-3})				
Urochloa brizantha	0.08 ± 0.02^{ns}	0.11 ± 0.09^{ns}	0.17 ± 0.05^{ns}	0.11 ± 0.02^{ns}	0.12 A**
Hemarthria altissima	0.06 ± 0.01	0.05 ± 0.04	0.13 ± 0.02	0.08 ± 0.01	0.08 B
Cynodon dactylon	0.06 ± 0.01	0.05 ± 0.02	0.10 ± 0.03	0.04 ± 0.01	0.06 B
Grass group average	0.07 B**	0.07 B	0.13 A	0.07 B	
	Total porosity (m^3 m^{-3})				
Urochloa brizantha	0.46 ± 0.01^{ns}	0.44 ± 0.07^{ns}	0.50 ± 0.03^{ns}	0.48 ± 0.02^{ns}	0.47 A***
Hemarthria altissima	0.41 ± 0.02	0.38 ± 0.02	0.48 ± 0.03	0.45 ± 0.01	0.43 B
Cynodon dactylon	0.40 ± 0.02	0.38 ± 0.01	0.43 ± 0.03	0.40 ± 0.01	0.40 C
Grass group average	0.42 BC***	0.40 C	0.47 A	0.44 B	
	Total organic carbon (g kg^{-1})				
Urochloa brizantha	7.11 ± 2.72 ^{ns}	8.35 ± 1.55 ^{ns}	10.64 ± 1.11 ^{ns}	13.92 ± 5.25 ^{ns}	10.00 ^{ns}
Hemarthria altissima	5.64 ± 1.36	5.90 ± 0.18	16.33 ± 10.96	13.99 ± 9.84	0.47
Cynodon dactylon	6.79 ± 1.71	4.81 ± 0.77	12.41 ± 1.96	9.59 ± 2.09	8.40
Grass group average	6.51 B**	6.35 B	13.13 A	12.50 A	

Means of grass species treatmetns followed by different lowercase letter within the column (time of restoration) differ statistically according to Tukey's test. Means at specific restoration time regardless of grass type (grass group average) and mean of a grass type regardless of restoration years (grass average) followed by different uppercase letter differ statistically according to Tukey's test. ns: not significant; *p < 0.10; **p < 0.05; ***p < 0.001.

statistically from each other and were lower compared to the Tp observed after 14.6 years (0.47 m^3 m^{-3}) (Table 4). After 20 years of restoration, this Tp average decreased significantly by 6 % to 0.44 m^3 m^{-3}, and it did not differ statistically from that observed after 0.5 years of restoration (Table 4). The grass average (regardless of restoration age) for soil Tp decreased statistically as follows: *Urochloa brizantha* (0.47 m^3 m^{-3}) > *Hemarthria altissima* (0.43 m^3 m^{-3}) > *Cynodon dactylon* (0.40 m^3 m^{-3}) (Table 4).

3.3. Soil TOC content

In the 0.00–0.10 m layer, the grass species group average (regardless of grass species) of soil TOC at 0.5 years (5.30 g kg^{-1}) remained statistically unaltered after 8.6 years of restoration (9.04 g kg^{-1}), increased significantly to 23.12 g kg^{-1} after 14.6 years but without further significant changes after 20 years of restoration (21.82 g kg^{-1}) (Table 3). In the 0.10–0.20 m layer, the same trend was observed. The grass species group average (regardless of grass species) of soil TOC after 0.5 years (6.51 g kg^{-1}) did not differ from that observed after 8.6 years (6.35 g kg^{-1}), increased significantly to 13.13 g kg^{-1} at 14.6 years, but without further significant changes after 20 years of restoration (12.50 g kg^{-1}) (Table 4).

3.4. PCA of minesoil attributes over the years

Component 1 and 2 of PCA explained 55.58 % and 27.17 %, respectively, of the variation in the dataset of the 0.00−0.10 m layer (Fig. 3a). In the 0.10−0.20 m layer, the component 1 and 2 of PCA explained 63.32 % and 18.49 %, respectively, of the variation of the dataset (Fig. 3b). In both layers, the right (positive) portion of PCA component 1 displays closer relations between Tp, Ma, microaggregates (%) and TOC eigenvectors mainly in the minesoil after 14.6 and 20 years of restoration (Fig. 3). The opposite (negative) portion of PCA component 1 displays the association of macroaggregates (%) and Bd eigenvectors with the minesoil restored for 0.5 and 8.6 years (Fig. 3). In both layers, most replicates of *Cynodon dactylon* and *Hemarthria altissima* treatment remained at the left (negative) portion of component 1 after 0.5 and 8.6 years of restoration, more closely associated to Bd and macroaggregate (%) eigenvectors (Fig. 3). In addition, even after 20 years of restoration, 2 and 4 out of the 4 replicates of *Cynodon dactylon* treatment of the 0.00−0.10 and 0.10–0.20 m layer, respectively, were still more strongly associated with macroaggregates (%) and Bd eigenvectors at the negative portion of component 1, like samples of other treatments with shorter restoration ages (Fig. 3). In contrast, two replicates of *Urochloa brizantha* treatment were already ordinated at the right (positive) side of component 1 after 8.6 years of restoration in both layers, more closely associated mainly with Ma, Tp, TOC and microaggregates (%), similar to most minesoil samples with 14.6 and 20 years of restoration (Fig. 3).

4. Discussion

4.1. Evolution of the minesoil structure and TOC over 20 years of restoration

The persistent compaction in the studied minesoil until 8.6 years of restoration is confirmed by the high percentage of macroaggregates (close to or > 90 %) in the 0.00–0.10 m (Table 3) and especially in the 0.10–0.20 m layer (Table 4), where it is accompanied by soil Bd values between 1.38 and 1.58 Mg m^{-3} (Table 4). These Bd values have been reported as restrictive to root growth in this minesoil (Pauletto et al., 2016). In this context, Guzman et al. (2019) reported a severe limitation to root development at a depth of 0.25 m in soils cultivated with maize, with the highest proportion of root biomass concentrated in the

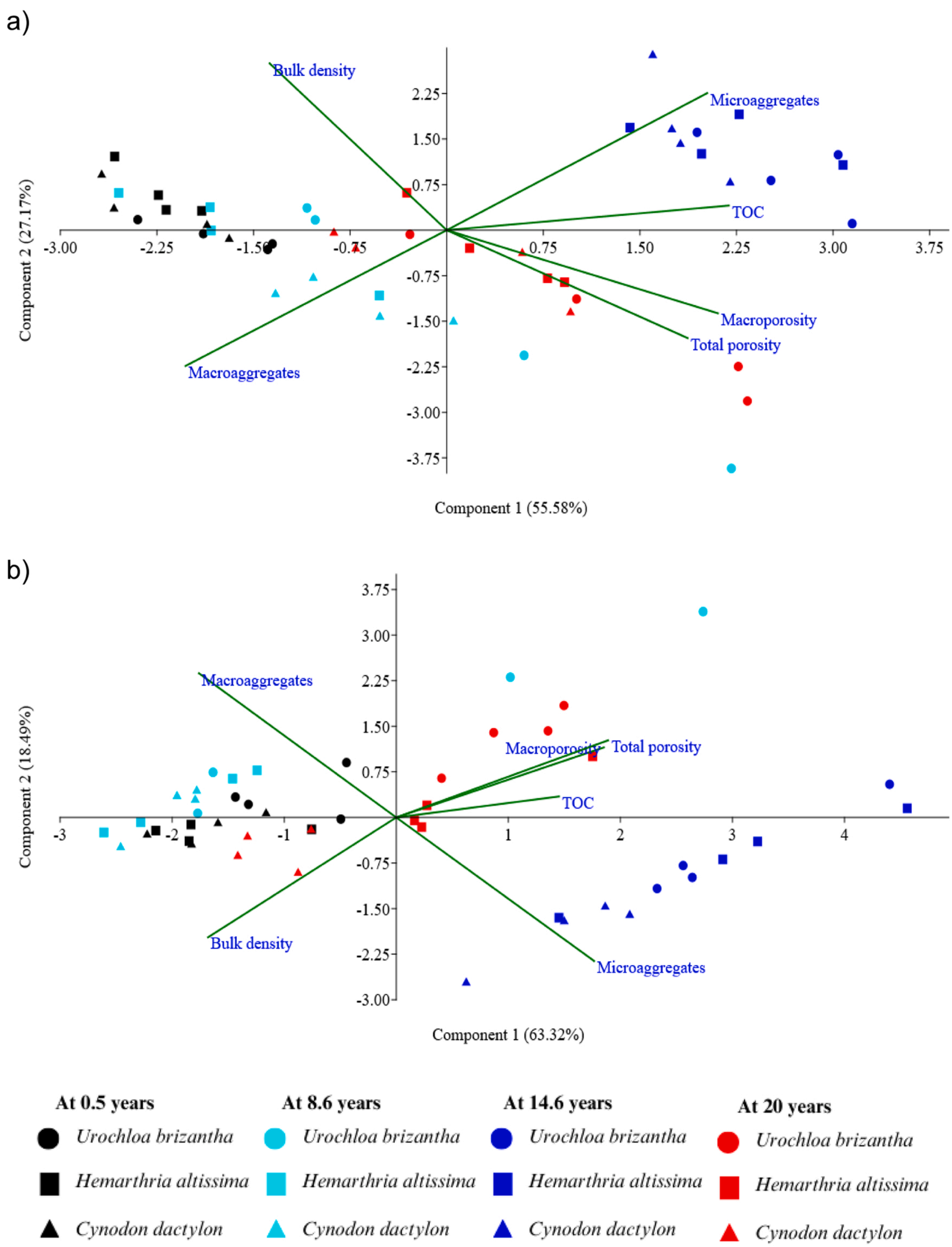

Fig. 3. Principal component analysis integrating macroaggregates, microaggregates, bulk density (Bd), macroporosity (Ma), total porosity (Tp) and total organic carbon (TOC) in the 0.00–0.10 m (a) and 0.10–0.20 m layer (b) at 0.5, 8.6, 14.6 and 20 years of restoration with perennial grasses (*Urochloa brizantha, Hemarthria altissima* and *Cynodon dactylon*).

0.00–0.20 m layer (90–95 %). Similarly, Stutler et al. (2022), when comparing four minesoil areas with different restoration periods (ranging from 2 to 32 years), observed that soil Bd remained high (1.34–1.37 Mg m^{-3}) up to 16 years of restoration, values comparable to those found in the present study up to 14.6 years (Tables 3 and 4). The authors reported lower Bd values only after 32 years of restoration (1.12 Mg m^{-3}).

It is important to highlight that the high macroaggregates percentage observed until 8.6 years of restoration in both layers (Tables 3 and 4) is likely attributed to the presence of compression-formed aggregates rather than to biogenic or physicogenic aggregates, which typically result from the intestinal tracts of soil macrofauna and root system activity, together with interactions among soil carbon, clay, cations, and wetting–drying cycles of the soil (Silva et al., 2023). The formation pathways and responses of these distinct aggregate types to soil management practices have been reported for agricultural soils and used as soil quality indicators (Pereira et al., 2021; Silva et al., 2023; 2025). At our experimental site, Stumpf et al. (2018a) confirmed a minority of physicogenic and biogenic aggregates and a large majority of compression-formed macroaggregates in this minesoil, the last being characterized by elevated tensile resistance and low organic carbon content. Such compressive aggregates in this area derive from the traffic of heavy machinery on soil during the topographic restoration of the landscape in 2003. This process may have been amplified by the clayey texture of the material used as topsoil in this area (Table 1). For instance, Da Silva Barboza et al. (2021) reported a critical compression of the topsoil of a minesoil after the initial machinery traffic, leading to an increase of the soil Bb by 23.5 % and 16.4 % in the 0.00–0.10 m and 0.10–0.20 m layer, respectively. Moreover, the authors reported an increase of 62 % in the macroaggregates percentage in the 0.00–0.10 m layer after twelve traffic events, which was accompanied by a proportional decline of microaggregate percentage as expected. The close relationship between high Bd and macroaggregate percentage values, especially noticed up to 8.6 years of restoration, as revealed by PCA (Fig. 3a-b), regardless of soil layer and grass type, emphasizes the legacy of heavy machinery traffic on soil structure. Likely, this hinders the reclamation of the mined land. This is in line with Liu et al. (2024), who found significant reduction of minesoil Bd only after 12 years of reclamation due to lasting soil compaction caused by the traffic of heavy machinery on minesoil during its formation.

The restoration of minesoil attributes does not occur linearly over time in initially compacted minesoils, as illustrated in Fig. 4. We consider that the structural restoration of the studied minesoil starts with the disaggregation of compression-formed macroaggregates into microaggregates (between 0.5 and 14.6 years), followed by the reaggregation of microaggregates into macroaggregates formed through natural processes (from 14.6 years onward). This sequence can lead to variable responses in other attributes, such as Bd and Ma. For instance, in our experimental area, during the early stages of minesoil recovery (< 10 years), the topsoil exhibited an extremely high proportion of compressive macroaggregates, even when the vegetation had already fully covered the area and despite the implementation of scarification practices at the beginning of the experiment, in late 2003 (Stumpf et al., 2016). Therefore, although the macroaggregates percentage was similar at 0.5 and 8.6 years in the 0.00–0.10 m layer (approximately 89 %), the Bd value measured at 0.5 years was high even after the scarification process performed shortly after minesoil reconstruction, whereas at 8.6 years, the observed Bd resulted from the interaction between root system expansion and the wetting–drying cycles typical of clayey soils (Fig. 4). Using *Urochloa brizantha* as an example, an initial decrease in Bd was observed in the 0.00–0.10 m layer (from 1.40 to 1.22 g cm^{-3} after 8.6 years), likely due to intense root activity that promoted fissures in the minesoil during the transformation of compressive macroaggregates into microaggregates (Stumpf et al., 2018a). Following this period, the soil Bd increased again (in absolute terms, though not statistically significant), reaching 1.32 g cm^{-3} at 14.6 years (Table 3). This increase may be associated with a new rearrangement of aggregates, particularly of microaggregates, influenced by fine root decomposition (a typical aspect of the life cycle of perennial grasses), organic matter inputs, and the filling of pores with fine particles induced by wetting–drying cycles. A subsequent slight decrease in Bd (also not statistically significant) to 1.27 g cm^{-3} at 20 years (Table 3) suggests the onset of a new phase of soil restructuring, likely driven by renewed root expansion and the input of root exudates, resulting in a higher proportion of biogenic macroaggregates (Fig. 4). These considerations warrant further investigation for clarification of potential trends.

The proposed minesoil restructuration concept (Fig. 4) follows up and adds knowledge to the hierarchy of aggregate formation in this minesoil proposed by Stumpf et al. (2016). According to the authors, this process consists of four steps: (1) formation of large, cohesive and extremely compacted aggregates due to intense traffic of heavy machinery during minesoil formation; (2) formation of smaller aggregates from the breakdown of the large and cohesive aggregates through the action of wetting and drying cycles and the early development of the plant root system; (3) appearance of cohesive microaggregates, sometimes covered by root fragments, as first signs of re-aggregation; (4) formation of new and large aggregates by the action of roots and microorganisms favoring the conglomeration of mineral and organic particles into microaggregates, with sequential stabilization of aggregates.

The unchanged TOC content in both 0.00–0.10 and 0.10–0.20 m layer up to 8.6 years of restoration (Tables 3 and 4), despite continuous minesoil revegetation including NPK fertilization and liming, reflects the constraint to plant development imposed by minesoil compaction, as well as the strong depletion and slow recovery of microbial functions

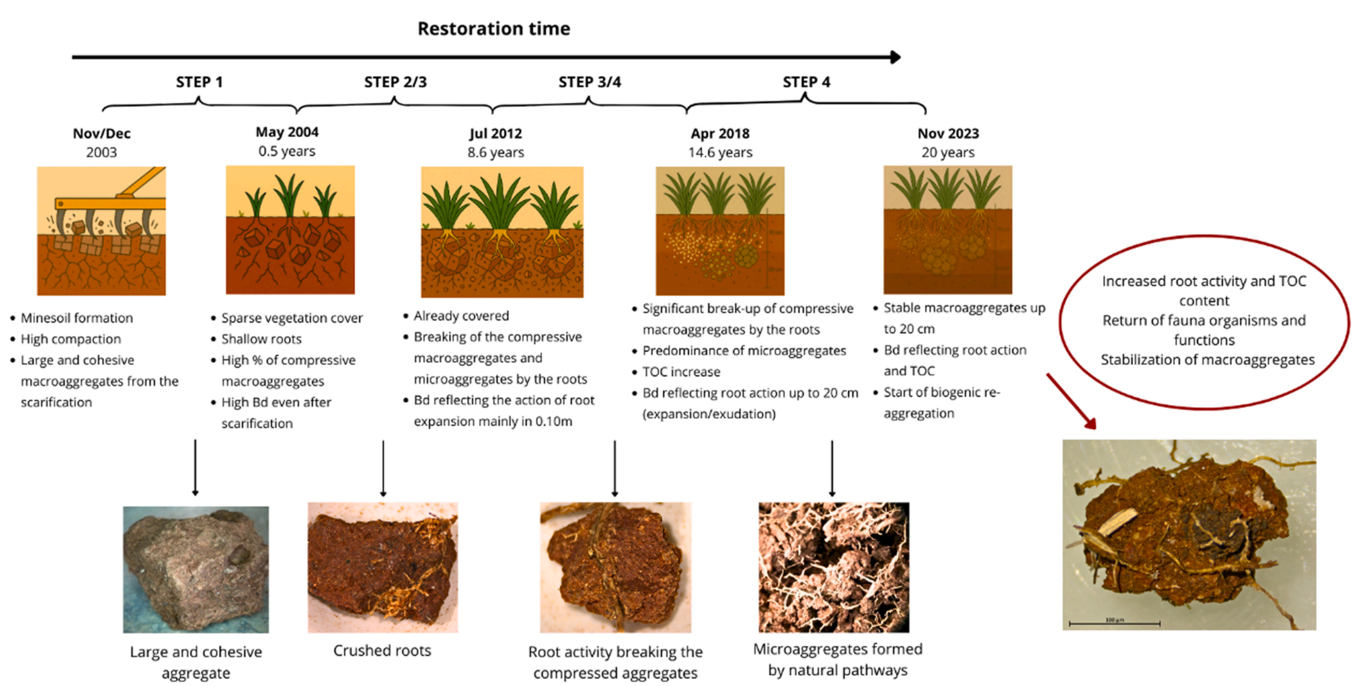

Fig. 4. Conceptual diagram of minesoil structural evolution over 20 years of restoration with perennial grasses in Candiota RS, Brazil.

associated with SOC accrual and stabilization in minesoils (Frouz et al., 2017; Kumar et al., 2018; Clayton et al., 2021). The abundance and diversity of bacteria and fungi in minesoils may increase with restoration age depending on restoration practices (Roy et al., 2017; 2023; Schmid et al., 2020), tending to promote soil aggregation and the protection of SOC against decomposition by its occlusion in aggregates and formation of organo-mineral complexes (D'Acqui et al., 2017; Li et al., 2018). Such trends have been reported for post-coal minesoils revegetated with grasses, agriculture, or forest species in contrasting environments (Šourková et al., 2005; Vindušková and Frouz, 2013; Zhang et al., 2019; Zhao et al., 2022).

It is important to highlight that at 14.6 years of restoration, there was a substantial accumulation of TOC in both soil layers, which remained unchanged up to 20 years (Tables 3 and 4). This accumulation coincided with a predominance of microaggregates over macroaggregates percentage, in contrast to observations at 20 years, when the macroaggregates percentage became predominant once again (Tables 3 and 4). These observations may support the idea that the breakdown of compressive macroaggregates occurrs mainly during the first 15 years, and that from this point onward, the biogenic formation of aggregates is promoted, ultimately indicating the return of ecosystem functions in the minesoil (Fig. 4).

4.2. Comparison of perennial grasses and implications for minesoil structure

The present study builds up on the aggregation model (Fig. 4) developed for this minesoil by revealing that steps 2 and 3 proposed by Stumpf et al. (2016) are likely to take place between 8.6 and 14.6 years of restoration, without distinction between the grass species. In addition, it is plausible to consider that the significant TOC increase between 8.6 and 14.6 years in both soil layers may favor the formation of physicogenic microaggregates and macroaggregates (Fig. 4). This process may result from the expansion of the root system through the minesoil profile (Stumpf et al., 2018a, 2018b; Feng et al., 2021) together with cycles of soil wetting and drying during these years (Totsche et al., 2018). In fact, Stumpf et al. (2016) demonstrated the presence of roots in the 0.10–0.20 m layer of this minesoil after 8.6 years of restoration, with root densities of 6.00, 2.71, and 2.01 Mg m^{-3} for *Urochloa brizantha*, *Hemarthria altissima* and *Cynodon dactylon*, respectively. Together, the data on macroaggregates percentage, TOC and roots suggest that step 4 proposed by Stumpf et al. (2016) (macroaggregate formation) of aggregation conceptualized for this minesoil (Fig. 4) occurs between 14.6 and 20 years of restoration, regardless of the soil layer, and without clear differentiation between the grass species.

The proposed timing of aggregation steps (Fig. 4) is strongly supported by the shift of soil samples from left to right in the PCA plot with restoration age, reflecting the alleviation of soil compaction along with increases in TOC, Ma and Tp (Fig. 3a-b), confirming the progressive improvement of minesoil structural quality (Miguel et al., 2023; Leal et al., 2025). Notably, soil samples after 20 years of restoration were ordinated around the plot center between microaggregate and macroaggregate (%) eigenvectors (Fig. 3), likely reflecting this disaggregation-reaggregation process (Fig. 4). In fact, this process was still not evident after 14.6 years of restoration as shown by the ordination of samples with this age of restoration closer to the microaggregate and consistently away from the macroaggregate eigenvector, regardless of grass species and soil layer (Fig. 3a-b), mostly assembling step 3/4 of aggregation (Fig. 4).

Among the grasses, it is noteworthy that *Urochloa brizantha* replicates with 8.6 years of restoration were grouped within the same PCA quadrant where most samples with 20 years of restoration were ordinated, regardless of soil layer (Fig. 3a-b). This demonstrates the remarkable adaptability of this grass to such heavily anthropized soil. *Urochloa brizantha* is widely used as a cover crop and pasture in Brazil and other South American countries, producing large amounts of aboveground biomass, which favors soil surface protection and SOC storage (Baptistella et al., 2020). In fact, Fernandez et al. (2023) demonstrated the superior performance of this species over the others to initiate favorable conditions for minesoil colonization by mesofauna and for SOM humification processes. The initial detrimental minesoil conditions for microorganisms may be a main driver limiting soil biological activity, as climate conditions may be favorable for soil organisms, e.g., consistent pattern of precipitation over years (Fig. 1). Thus, success of plant establishment in early restoration ages may be closely related to the return of soil biological functions. Moreover, such accelerated capacity of *Urochloa brizantha* roots to explore the minesoil may improve the recovery of essential elements from deeper layers before they are leached by the high annual precipitation typical in this region, thereby favoring the development of plants and soil microbial functions essential for its ecological restoration. Although the TOC and physical properties of the minesoil were similar between the different grass species after 20 years of restoration, this and other possible temporal benefits of revegetating the minesoil with *Urochloa brizantha* deserve future investigation. Although *Urochloa brizantha* is not native to the Pampa biome, it significantly improves the physical, chemical, and biological properties of minesoils compared to spontaneous vegetation (Fernandez et al., 2023), while integrating well into this grassland biome.

According to Article 225, Chapter 6 and § 2 of the Brazilian Federal Constitution, those who exploit mineral resources (i.e., mining companies) are obligated to restore the degraded environment in accordance with technical solutions recommended by the competent public authority (Federal Constitution of Brazil, 1988). Therefore, our findings are a relevant contribution to the establishment of successful minesoil restoration strategies in Brazil, particularly in Candiota.

5. Conclusions

The elevated percentage of macroaggregates (close to or exceeding 90 %) and Bd (close to or exceeding 1.50 Mg m^{-3}) observed in the 0.00–0.10 and 0.10–0.20 m layer of the minesoil up to 8.6 years of restoration reflect the lasting effects of heavy machinery traffic on minesoil during its reconstruction. Such severe compaction was attenuated by the different grass species used in this experiment after 14.6 years of restoration, as revealed by the transient reduction followed by an increase of macroaggregate percentage. This was assigned to root-induced disruption of aggregates formed by compression followed by soil re-aggregation. This was accompanied by a reduction of soil Bd and an increase of soil Ma and TOC at the same restoration age. Among the grasses, *Urochloa brizantha* promoted an accelerated restoration of soil structure, especially regarding the disruption of aggregates formed by compression in the 0.00–0.10 m layer, resulting in a decrease in macroaggregate and increase in microaggregate percentage as observed after 8.6 years of restoration. Additional benefits of such accelerated minesoil restoration (e.g., recovery of soil biological functions, attenuation of nutrient leaching and soil erosion) merit future studies. After 14.6 and 20 years of restoration this advantageous effect of *Urochloa brizantha* was mostly equalized with the other grass species, contradicting our hypothesis.

Overall, *Urochloa brizantha* is well adapted to the highly anthropized minesoils and subtropical climate of the Pampa Biome, Brazil, and may serve as an effective tool for the initial reintegration of these mined areas into the landscape, while promoting soil decompaction and TOC levels comparable to the other grasses in the long-term.

CRediT authorship contribution statement

Fernandez Maria Bertaso de Garcia: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **dos Anjos Leal Otávio:** Writing – review & editing, Supervision, Data curation. **Oliveira Islabão Gláucia:** Methodology, Formal analysis, Data curation. **Pagani Junior Adão:** Methodology, Data curation. **Vaz**

de Melo Tainara: Methodology, Data curation. **Knapp Ana Paula:** Methodology, Formal analysis. **Wenske Haudt Istefani:** Methodology, Formal analysis, Data curation. **Meireles de Farias Emerson:** Methodology, Formal analysis, Data curation. **Spinelli Pinto Luiz Fernando:** Project administration, Data curation. **Miguel Pablo:** Project administration, Data curation. **Rosa de Oliveira Jakeline:** Project administration. **Brüggemann Nicolas:** Writing – review & editing. **Alves Brito Pinto Marilia:** Writing – original draft. **Stumpf Lizete:** Writing – original draft, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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