Chapter

Reclamation of Soils Degraded by Surface Coal Mining

Luiz Fernando Spinelli Pinto, Lizete Stumpf, Pablo Miguel, Leonir Aldrighi Dutra Junior, Jeferson Diego Leidemer, Lucas da Silva Barbosa and Mauricio Silva e Oliveira

Abstract

The largest Brazilian coal mine, called Candiota mine, is located in South Brazil, with an estimated reserve about 1.2 billion tons. Since late 2003, an experiment located at a reclaimed site in a coal mining area was conducted, in which a research group from the Federal University of Pelotas has been conducting a long-term experiment on soil quality with different plants species, such as *Hemarthria altissima*, *Paspalum notatum* cv. Pensacola, *Cynodon dactylon* cv. Tifton, and *Urochloa brizantha*. After 8.6 years of revegetation, soil samples at 0.20 depth were collected in minesoil and natural soil to determine physical attributes, and the organic carbon content. After 10.9 years of revegetation, soil samples at 0.10 m depth were collected to determine the biological attributes. According to the research results, it can be seen that the recovery of minesoil was more effective after 8.6 years of revegetation only in the physical condition up to 0.10 m depth. However, all soil physical attributes and organic matter content are still below the levels observed in the natural soil. The biological attributes after 10.9 years of revegetation have not yet been sufficient to restore a mites and springtails population close to the natural soil.

Keywords: minesoil, revegetation, physical attributes, organic matter content, edaphic mesofauna

1. Why this study is important?

"Soil" is borne as a result of lengthy natural processes over thousands of years; hence, it is a valuable nonrenewable commodity. It is a basic environment needed for vegetation growth on land, be it a mined land or other. In case of soils degraded by surface coal mining, one should not bear in mind it would be a simple task to bring back degraded/mined soil to its near original configuration so that it would become naturally capable to sustainably support vegetation. With this aim, we carried out our study and here lies the "time period to bring back the degraded minesoil to close to natural soil condition," which is an extremely important requirement for surface coal mining successful closure. This research study has put stress on the long-time scientific evaluation of coal mine soil degraded by the excavation operation, i.e., mining (for more than 16 years). Though maintaining such experiment requires lot of efforts and resources, we think it is a necessary tool to analyze the question we have just put forward.

Our study was done in a randomized block design field experiment, sampling the same soil over the time, and comparing the soil properties with the natural soil, what makes the data obtained more scientifically reliable and meaningful. We, as authors, have tried to make this idea more clear in our writing; it is well known and obvious that the soils properties once covered with vegetation will tend to improve over time. Nevertheless, this does not necessarily happen, and sometimes, many sites show signs of degradation and even erosions problems after many years of reclamation, needing re-intervention.

Therefore, the main difference between our study and other similar studies is that of experimental control. Most studies deal with sampling of mining sites, with different ages, but without experimental control. It is also important to do research on soil reclamation techniques and procedures focusing on improving minesoil quality, ensuring the return of a productive soil according to the planned use.

2. Soils formed in surface coal mining

Coal remains a major fuel in global energy systems, accounting for almost 40% of electricity generation, and over the next 5 years, the global coal demand is forecasted to remain stable, supported by the resilient Chinese market, which accounts for half of the global consumption [1]. World coal reserves have a volume of approximately 860 billion tons, with deposits distributed in 75 countries. Of the existing reserves, 75% are concentrated in five countries: the United States, Russia, China, Australia, and India.

Brazil has one of the largest reserves of mineral coal in Latin America [2], and in recent years, it has been regaining its space in the energy market due to the need to supply the scarcity of electricity generated by water resources (due to seasonal lowering of water in the reservoirs). In Southern Brazil, the largest deposit in the country called Candiota Deposit is located, in which reserves of 1.2 billion tons are capable of being surface mined, at depths of up to 50 m [3].

The sequence of surface coal mining involves the previous removal of the original soil horizons, to then remove overburden rocks (**Figure 1a**,**b**, respectively). After coal seams extraction, the topographic reconstruction occurs, in which there is the return of the overburden rocks to fill the previous stripped area, and finally, the surface is leveled and topsoil is deposited to finish topographic recomposition (**Figure 1c**,**d**, respectively), creating an anthropogenic soil (**Figure 1e**).

Anthropogenic soils are soils that have been influenced, modified, or created by human activity. They are found worldwide in urban and other human-impacted landscapes. Four distinct types of anthropogenic soils can be distinguished based on geographical setting and historical context: (i) agricultural, (ii) archeological, (iii) mine-related, and (iv) urban [5]. According to the World Reference Base (WRB) [6], anthropogenic soils found in agricultural and archeological settings are classified as Anthrosols, whereas those in mine-related and urban settings are classified as Technosols. Anthrosols are formed by the transformation of natural soil by human additions of organic or inorganic materials over long periods of time, while Technosols are formed in parent materials created and deposited by human activities (e.g., mine spoils, urban fill). The most extensive mine-related anthropogenic soils are primarily associated with modern landscapes created by the surface mining of coal, and are classified as Spolic Technosols, according to the WRB, based on the fact that they contain technogenic artifacts in the form of mine spoil [5].

Before 1970s soil survey reports in the USA identified mined lands on maps and referred to them as mine dumps, mine spoils, or strip mines and mine-land reclamation its grouped surface materials on mined lands into various categories to assist

Figure 1.
Coal mining process (a-b) and topographic restoration (c-e) in southern Brazil [4].

with treatment for revegetation [7]. In the 1970s, after the passage of the Surface Mining Control and Reclamation Act (SMCRA) of 1977 and the resultant state permanent regulatory programs, coal mined lands were mandated to be returned as close as possible to the approximate original landscape, and since successful revegetation was rigorously required, natural topsoil, or a topsoil substitute (in case of the pre-1970s mining), was placed at the final reclamation surface [8]. Modern mining regulations also started to require the isolation of acid-producing (FeS_2) materials below the final surface. Since then, these soils, resulting from the reclamation process, have been called in the USA as minesoils [7, 9, 10], or less frequently as mine soils [8].

Minesoils, as the result of the mining and reclamation process, compared to the contiguous native soils, are much younger soils with properties more determined by human-controlled influences rather than by natural processes [9]. Their profile morphology can roughly be described as mainly composed of two layers, a surface layer made by the topsoil (the native soil A horizon) abruptly lying over a overburden layer. After few years of revegetation and exposure to climatic conditions, even in topsoil substitute layers, these young A horizons start to be loosened by root growth and organic matter accumulation and decomposition, developing color darkening and some soil structure. Also, the surface mining may accelerate the soil-forming processes by breaking up the consolidated rocks of the overburden layers allowing air, water, and plant roots to penetrate this layer [6]. Therefore, in strict pedological description of horizons, usually A-C horizon sequences in very young soils (<10 years old) and A-AC-C sequences in relatively older soils (>10 years old) are found. In some older profiles (>30 years old), the beginning of formation of B horizons (Cambic) has been reported [9].

The topsoil addition surely improves the minesoil quality, but heavy machinery traffic and inadequate soil distribution can hinder the vegetation development, the main starting point for the minesoils recovery [11]. As the consequence of excessive traffic from large machines during topographic recomposition, persistent topsoil compaction (**Figure 2a**,**b**) has been reported as a major impact on the physical quality of minesoils in India [12], in China [13], in UK [14], in South Africa [15], in Germany [16], in the USA [17], and in Brazil [18].

The development and evolution of the reclaimed minesoil provides a unique opportunity to expand the existing knowledge about the formation and stabilization of aggregates, accumulation and distribution of organic matter and microbial biomass, since, due to the magnitude of the disturbance of the ecosystem, it creates a sort of "zero time" scenario [19]. The success of the minesoil recovery does not only depends on the mining methods, the height and slope of the overburden piles, the nature of the mined soils, the geoclimatic conditions, but also depends on the plant species selected for their revegetation [20]. In this sense, a great number of plant species have been researched as an alternative to recover the quality of coal minesoils in different places in the world, some of which are cited below.

2.1 Reclamation of minesoils and revegetation in the USA

Soil and plant data among a chronosequence of 19 post-mine reclaimed sites (over a 40-year reclamation gradient), and an intact native reference site were evaluated. It was noticed that root biomass in the upper horizons (at 30 cm depth) was greater on the reference site compared with the reclaimed sites as well as the

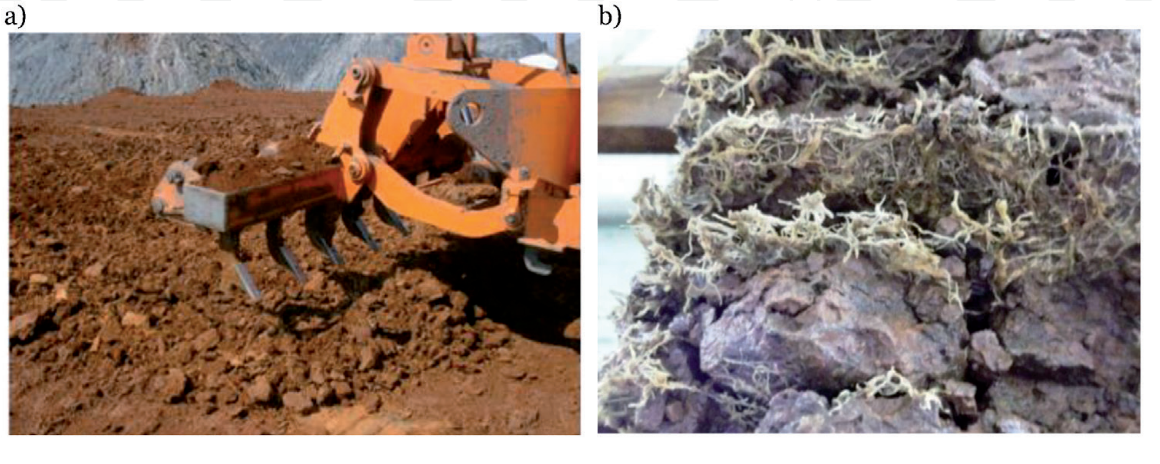

Figure 2.
Compaction of topsoil immediately after topographic restoration of the minesoil (a) and after 8.6 years of revegetation in southern Brazil (b) [4].

organic matter content, ranging from 3·5 to 5·4% on the reclaimed sites (not different across the reclamation chronosequence) and from 5·1 to 6·8% on the reference site [21]. On the other hand, in the Midwestern USA, there was the development of horizons in minesoils in a relatively short period of time (10–15 years), in which the 0.00–0.03 m layer consisted of non-decomposed or partially decomposed organic matter, while the 0.03–0.10 m layer was darker, with visible addition of organic carbon, and the 0.10–0.25 m layer was the least colored with interspersed roots [22]. When opting for the natural revegetation of mined areas, it was observed that minesoils up to 2 years of age have a predominance of annual and perennial grasses, while minesoils with 16–20 years usually have some tree species, and minesoils with 38–42 years old have a mix of native trees and understory species [23].

2.2 Reclamation of minesoils and revegetation in China

Vegetation succession and soil characteristics under five different restoration models of refuse dumps including different-aged revegetated sites were evaluated. It was observed that the biomass of the naturally species increased from 0.15 kg m^{-2} in the 8-year-old vegetation to 0.64 kg m^{-2} in the 18-year-old vegetation. Furthermore, the soil bulk density decreased from 1.56 Mg m^{-3} in 8-year-old vegetation on the abandoned land to 1.24 Mg m^{-3} for 18-year-old vegetation [24]. In another study, the minesoil showed improvements in its edaphic quality after 5 years of revegetation, which promoted an increase in the content of organic matter and a reduction in runoff and soil erosion. [25]. On the other hand, the positive effects of revegetation on microbial activity were observed over 18 years of minesoil's formation [26].

2.3 Reclamation of minesoils and revegetation in other countries

In India, carbon dynamics in one unreclaimed site (0 years) and four chronosequences revegetated coal mine sites (3, 7, 10, and 15 years) were compared with an undisturbed forest as a reference site. It was verified that soil organic carbon stock significantly increased from 0.75 Mg C ha^{-1} in 3 years to 7.60 Mg C ha^{-1} after 15 years of tree species revegetation in the top 15 cm of soils [27].

In Spain, the effectiveness of using native colonizer shrubs as nurse plants to reintroduce the two main tree species present before the mining operations was evaluated. It was found that the seedlings mortality under shrubs increased during the second year after plantation, probably because of the lower precipitations during the second growing season that reduced the water holding capacity of then minesoil (1–3.5 g cm^{-2}) when compared with the nearby natural forest soil (19.8 g cm^{-2}) [28].

In southeastern Nigeria, minesoils under 30 years of natural revegetation still lacked an O horizon and high values of soil density in relation to natural soil [29].

In Germany, it was observed that minesoils after 4 years of revegetation still showed very variable physical properties, and that the choice of perennial species with deeper rooting was recommended to accelerate the formation of the new soil structure [16].

2.4 Reclamation of coal minesoils and revegetation in southern Brazil

Minesoils that use little topsoil thickness give rise to contamination with the fragments of overburden rocks, frequently showing high soil bulk density, lower macroporosity, and high mechanical resistance to penetration, in addition to spots with very low pH values (<3.0) [30].

Attributes of minesoil under the cultivation of *Hemarthria altissima*, *Paspalum notatum* cv. Pensacola, *Cynodon dactylon* cv. Tifton, and *Urochloa brizantha* were evaluated in a randomized block design experiment at 5 [31], 41 [32], 72 [33, 34], 78 [35], and 103 months [36]. The results are reported below:

a. At 5 months of revegetation, there were no differences in the attributes of the minesoil under the different species. However, the highest concentration of aggregates in the 0.00–0.10 m layer occurred in the 1.00–0.25 mm class (32.67%), while in the 0.10–0.20 m layer, the highest concentration occurred in the 4.76–2.00 mm class (26.68%). The average carbon content in the 0.00–0.10 m layer was 5.34 g kg^{-1} and in the 0.10–0.20 m layer, it was 5.18 g kg^{-1}.

b. At 41 months of revegetation, there were also no differences in soil attributes under the different species. However, the highest concentration of aggregates occurred in the 1.00–0.25 mm class, both in the 0.00–0.10 m layer (40.13%) and in the 0.10–0.20 m layer (35. 73%). The average organic carbon content in the 0.00–0.10 m layer was 7.38 g kg^{-1} and in the 0.10–0.20 m layer, it was 6.20 g kg^{-1}.

c. At 72 months of revegetation, in the 0.00–0.05 m layer, the lowest value of the pre-consolidation pressure was provided by *Hemarthria altissima* (71 kPa) while the other plant species showed higher values provided: *Paspalum notatum* cv. Pensacola (120 KPa), *Cynodon dactylon* cv. Tifton (120 kPa), and *Urochloa brizantha* (118 kPa).

d. Also at 72 months of revegetation, in the 0.00–0.03 m layer, it was observed that *Hemarthria altissima* and *Urochloa brizantha* provided the highest carbon stocks in the light free fraction (1.22 Mg ha^{-1} and 1.27 Mg ha^{-1}, respectively) compared to *Paspalum notatum* (0.86 Mg ha^{-1}) and *Cynodon dactylon* (0.83 Mg ha^{-1}). In relation to the carbon stock of the light occluded fraction, *Hemarthria altissima* and *Cynodon dactylon* presented higher stocks (1.09 Mg ha^{-1} and 1.02 Mg ha^{-1}, respectively) compared to *Paspalum notatum* (0.61 Mg ha^{-1}).

e. At 78 months of revegetation, it was found that concentration of macroaggregates was higher in the 0.10–0.20 m layer (87.56%) compared with the 0.00–0.10 m layer (81.15%). Average organic carbon content in the 0.00–0.10 m layer was 8.46 g kg^{-1} and in the 0.10–0.20 m layer, it was 6.39 g kg^{-1}.

f. After 103 months of revegetation, root's perennial grasses concentration and minesoil physical attributes were measured. It was verified that the root mass 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, due to inadequate physical conditions below the 0.00–0.10 m layer, indicated by macroporosity values below 0.10 m^3 m^{-3}, bulk density greater than 1.40 Mg m^{-3}, and the highest percentage of macroaggregates with large, cohesive, and sharp-edged aggregates features. In relation to this, a different soil-aggregation hierarchy path in clay minesoils with highly compacted topsoil was proposed, in which, prior to revegetation, compacted aggregates arising from the compression of the soil mass made by the intense movement of heavy machinery were produced during topographical recomposition. Thus, in the first year after revegetation, the 0.00–0.10 m soil layer presented smaller aggregates arising from the breakdown of the large cohesive aggregates than the 0.10–0.20 m layer. From this point on, aggregation would begin to develop with the action of decomposed roots and microorganisms favoring the conglomeration of particles, with sequential reformation and stabilization of aggregates, following the traditional soil-aggregation hierarchy path. As the root system progressively reaches and develops in the 0.10–0.20 m layer, the same process mentioned above is expected to occur. It is important to mention that all hierarchical levels mentioned above can occur simultaneously within the same layer of the minesoil.

3. Physical and biological attributes of minesoil revegetated with perennial grasses compared with the natural soil in southern Brazil: a case study at the Candiota coal mine

In late 2003, a field experiment located at a reclaimed site in the Candiota coal mine (31°33′56″ S and 53°43′30″ W) was implemented, under concession of the Riograndense Mining Company, and the research group from the Pelotas Federal University has been conducting a long-term experiment on the soil quality with different plants species.

The topsoil used to cover the coal overburden was composed mainly by the B horizon of the natural soil (prior to mining), a Rhodic Lixisol [6], with high clay content (466 g kg^{-1} clay), dark red color (2.5 YR 3/6), and lower organic matter content (12 g kg^{-1}) compared to the A horizon (21 g kg^{-1}). The experiment was installed in November/December 2003 in a randomized block design with four replicates (each plot with 4 × 5 m = 20 m^2). Grasses used as treatments consisted of perennial summer grasses (**Figure 3**): *Hemarthria altissima* (15 cuttings m^{-2}), *Paspalum notatum* cv. Pensacola (50 kg of seed ha^{-1}), *Cynodon dactylon* cv. Tifton (15 cuttings m^{-2}), and *Urochloa brizantha* (10 kg of seed ha^{-1}). Prior to the implantation of the cover crops, the soil was chiseled with a bulldozer up to 0.15 m depth, and also received dolomitic limestone equivalent to 10.4 Mg ha^{-1} effective calcium carbonate rating and 900 kg ha^{-1} of NPK fertilizer, 5-20-20 (45 kg N, 180 kg P_2O_5, and 180 kg K_2O). Annually, all plots received 250 kg ha^{-1} of NPK fertilizer, 5-30-15 (12.5 kg N, 75 kg P_2O_5, and 37.5 kg K_2O) and 250 kg ha^{-1} of ammonium sulfate.

In July 2012 (8.6 years of revegetation), soil samples in the 0.00–0.10 m and 0.10–0.20 m layers were collected in minesoil and natural soil to determine the granulometry [37], tensile strength [38, 39], distribution of water stable aggregates in size classes [40, 41], bulk density and soil porosity, and the organic carbon content [42]. In October 2014 (10.9 years of revegetation), the soil samples in the 0.00–0.10 m layer were collected to determine the microbial biomass carbon [43], metabolic quotient [44], and organisms of the edaphic mesofauna, represented by mites and springtails [45]. All soil attributes differences were compared to the natural soil under native vegetation (reference soil).

The predominant natural soil of the mining area is a Rhodic Lixisol with 477.79 g kg^{-1} sand, 271.81 g kg^{-1} silt, and 250.40 g kg^{-1} clay in the 0.00–0.10 m layer, and 444.91 g kg^{-1} sand, 256.09 g kg^{-1} of silt, and 299.00 g kg^{-1} of clay in the 0.10–0.20 m layer [4]. Due to the soil construction processes, both the 0.00–0.10 and 0.10–0.20 m layers of the minesoil present, respectively, 80.91 and 59.87% higher clay content (453 and 478 g kg^{-1}, respectively) than the non-anthropized natural soil. Differences in clay content can make attribute comparisons between minesoils and natural soils questionable, as higher clay contents contribute to greater aggregation through the reorientation of clay particles, binding with root exudates and wetting and drying cycles. By contrast, measuring soil attributes prior to coal mining allows one to understand the intensity of the impact of mining

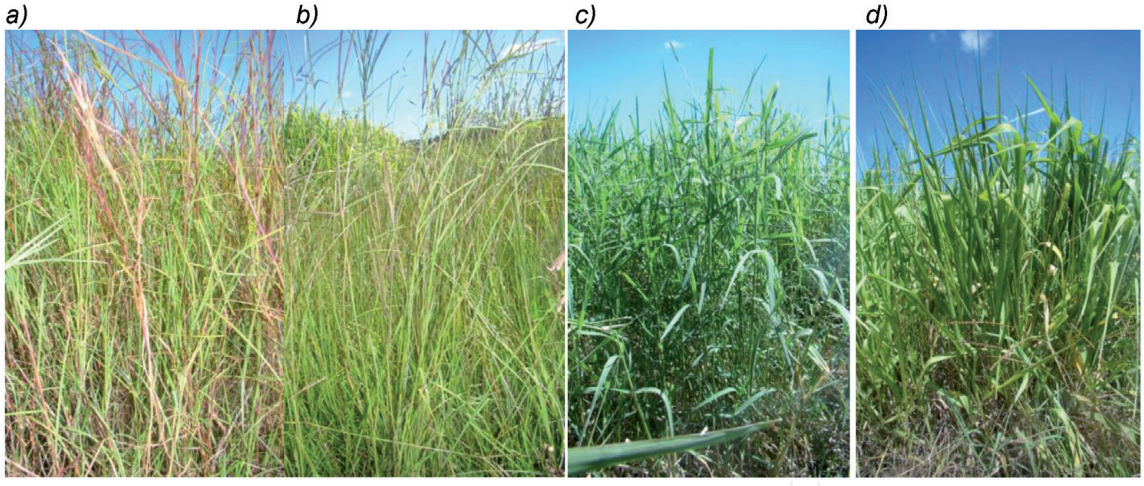

Figure 3.
Hemarthria altissima (a), Paspalum notatum cv. Pensacola (b), Cynodon dactylon cv. Tifton (c), and Urochloa brizantha (d) implanted in minesoil in southern Brazil [4].

on the environment. Consequently, the differences between the attributes of the natural and the minesoil are important in estimating the recovery period required for the new soil profile to perform functions in the environment in which it is inserted.

In this sense, after 8.6 years of revegetation, it is possible to observe that the minesoil under *Urochloa brizantha* and *Paspalum notatum* presented in the 0.00–0.10 m layer, respectively, 1.8 and 5.7% lower percentages of macroaggregates, while the constructed soil under *Hemarthria altissima* and *Cynodon dactylon* presented, respectively, 2.4 and 3.5% higher percentages of macroaggregates in relation to the natural soil (89.15%). In the 0.10–0.20 m layer, the treatments presented 16.4–19.2% higher percentage of macroaggregates in relation to the reference soil (80.65%) (**Figure 4a**). The largest proportion of macroaggregates presented by minesoil below the 10 cm layer, relative to natural soil, does not refer to a natural aggregation process promoted by biological forces (roots and exudates of microorganisms), but formed by the compression generated by intensive machines traffic during the topographic recomposition of the mined area [36].

Regarding the percentage of microaggregates, it was observed that in the 0.00–0.10 m layer, *Urochloa brizantha* and *Paspalum notatum* promoted, respectively, 46.9 and 14.9% higher percentage, while *Hemarthria altissima* and *Cynodon dactylon* promoted, respectively, 19.5 and 18.5% lower percentage than the reference soil (10.85%). In the 0.10–0.20 m layer, the treatments presented 68.6–80.2% lower microaggregation than the natural soil under native vegetation (19.35%) (**Figure 4b**). In a minesoil in the USA [39], macroaggregation was 50% smaller and microaggregation was 10% smaller in less than 1 year old soil (64% sand, 22% silt, and 19% clay) when compared to natural soil (55% sand, 29% silt, and 16% clay). However, after 16–20 years of revegetation, there was similarity between the distribution of minesoil aggregates (56% sand, 31% silt, and 13% clay) in relation to soils not disturbed by coal mining (59% sand, 28% silt, and 13% clay).

Figure 5 shows that in the minesoil under the perennial grasses, the aggregates presented 24.9–66% higher tensile strength compared to the natural soil (55.98 kPa) in the 0.00–0.10 m layer, while in the 0.10–0.20 m, the tensile strength values of the treatments were 163.9–221% higher than the reference soil (66.28 kPa). Similar results in a coal minesoil after 2.8 years of revegetation was observed, with higher tensile strength values in the 0.00–0.05 m (70.32–88.81 kPa) and 0.10–0.15 m (70.90–125.92 kPa) layers of grass covered in comparison to the natural soil under

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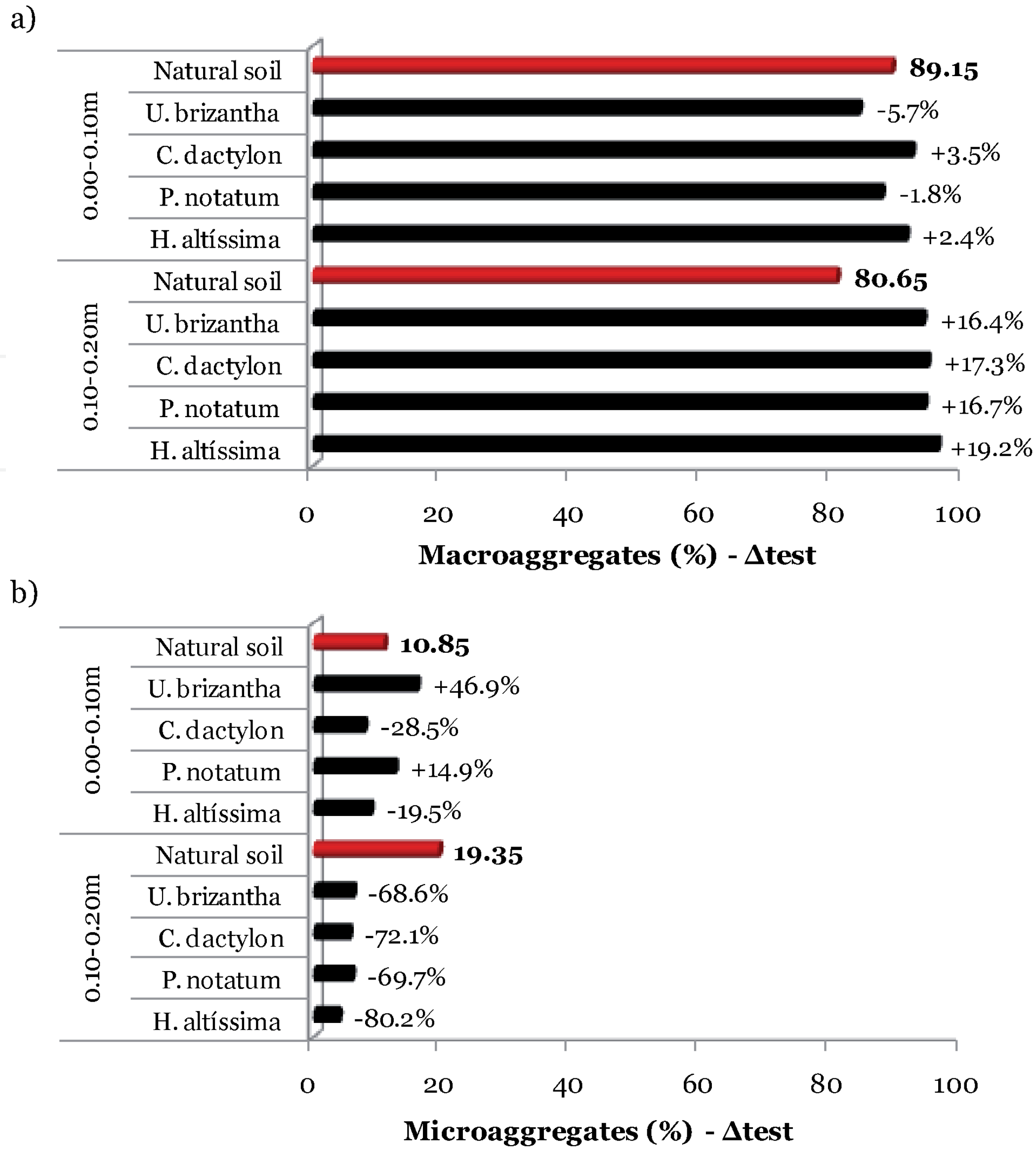

Figure 4.
Differences (Δtest) between percentage macroaggregates (a) and microaggregates (b) of minesoil after 8.6 years of revegetation (under perennial grasses) relative to natural soil (under native vegetation).

native vegetation (0.00–0.05 m: 55.98 kPa, and 0.10–0.15 m: 66.28 kPa) [46]. The higher tensile strength of aggregates is due to the effect of machine traffic during the topographic recomposition of the area, which resulted in cohesive, hard, and poor porous aggregates [38].

After 8.6 years of revegetation, it was also observed that the minesoil under different perennial grasses presented soil bulk density up to 21.1% higher in the 0.00–0.10 m layer, while in the 0.10–0.20 m layer, the difference was 15.7–34.05% in relation to the natural soil under native revegetation (presented 1.20 Mg m^{-3} and 1.18 Mg m^{-3}, respectively) (**Figure 6**). This result is due to topsoil compaction during the topographic recomposition of the mined area, commonly cited in the literature [47]. On the other hand, other studies indicate that the bulk density decreases over time, as observed in a minesoil in the USA, which is presented at 5, 10, and 16 years of revegetation values of 1.82 Mg m^{-3} (69% sand, 21% silt, and 10% clay), 1.70 Mg m^{-3} (50% sand, 28% silt, and 22% clay), and 1.48 Mg m^{-3} after 16 years (44% sand, 32% silt, and 24% clay). However, even after 16 years of revegetation, the bulk density was higher than the natural soil under grass (1.26 Mg m^{-3}) [48].

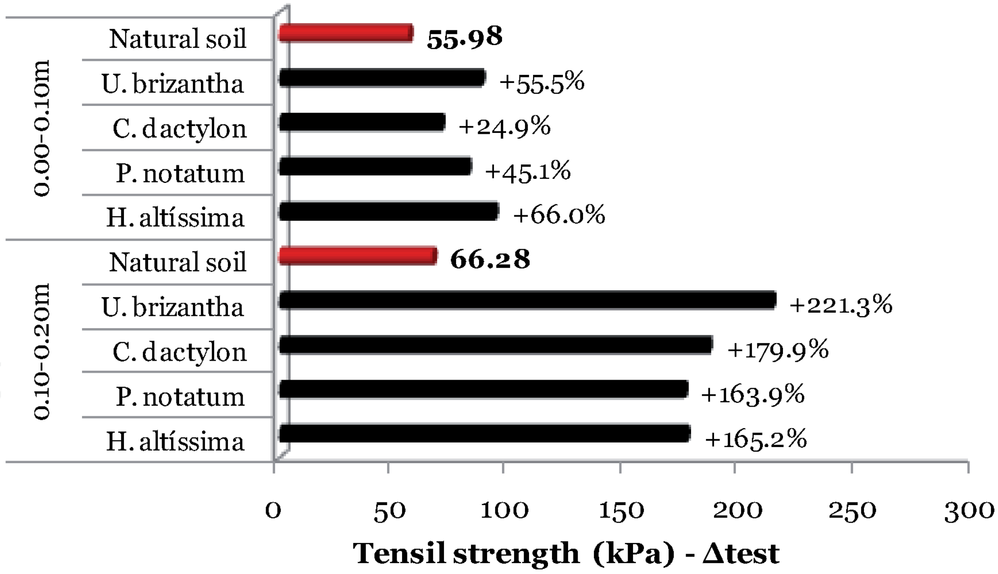

Figure 5.
Differences (Δtest) between tensile strength aggregates of minesoil after 8.6 years of revegetation (under perennial grasses) relative to the natural soil (under native vegetation).

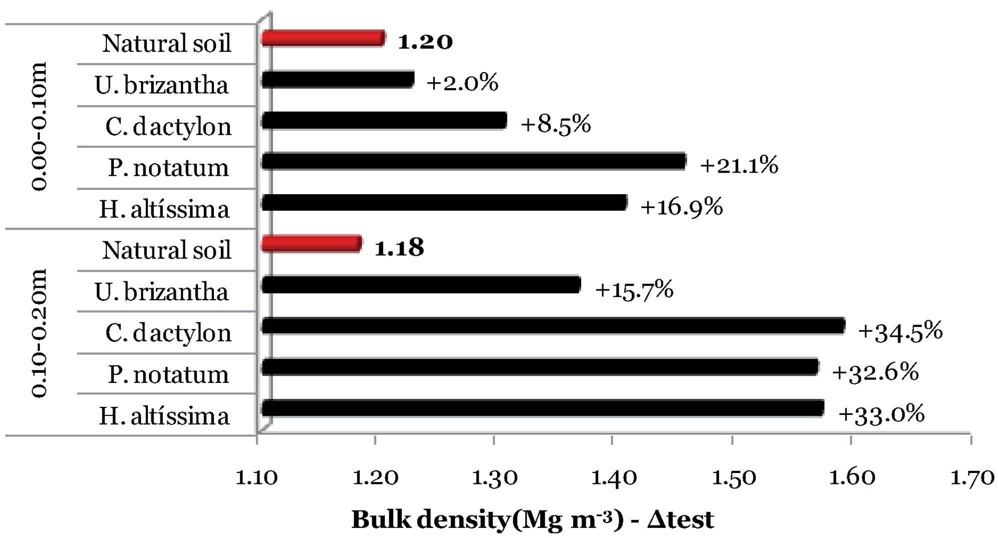

Figure 6.
Differences (Δtest) between the bulk density of minesoil after 8.6 years of revegetation (under perennial grasses) relative to the natural soil (under native vegetation).

When evaluating pore distribution, it was observed that in the 0.00–0.10 m layer, the minesoil under *Urochloa brizantha* and *Cynodon dactylon* presented, respectively, 26.4 and 25.9% higher macroporosity than the natural soil under native vegetation, while the other species presented lower values, highlighting the potential of the root system of these species, which presented in the layer of 0.00–0.10 m 92 and 93% of their roots with a diameter smaller than 0.49 mm [18]. However, below the 0.10–0.20 m layer, it was observed that the treatments presented 4.9–70.5% lower macroporosity than the reference soil (**Figure 7**), which was the consequence of the higher degree of compaction of minesoil.

The results presented show the difficulty in revegetating mined areas and, consequently, in allowing the natural incorporation of organic waste in the minesoils [49], which directly influences the regeneration of these areas. **Figure 8** shows that the organic carbon content of the minesoil was 48.3–58.2% lower in the 0.00–0.10 m layer compared to the natural soil (20.04 g kg^{-1}), while in the 0.10–0.20 m layer, the values were 18.6–53.1% lower than the natural soil (10.26 g kg^{-1}).

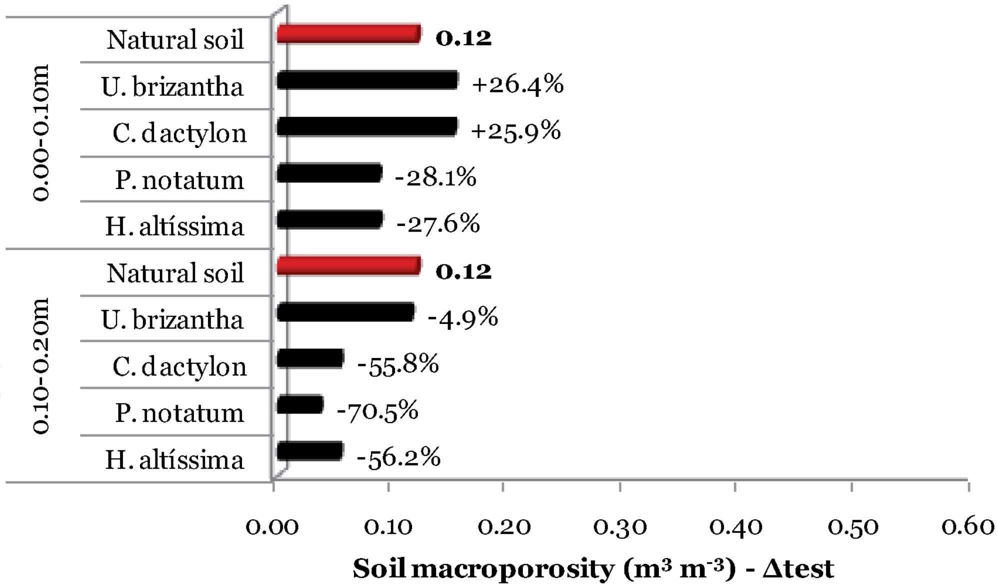

Figure 7.
Differences (Δtest) between the macroporosity of minesoil after 8.6 years of revegetation (under perennial grasses) relative to natural soil (under native vegetation).

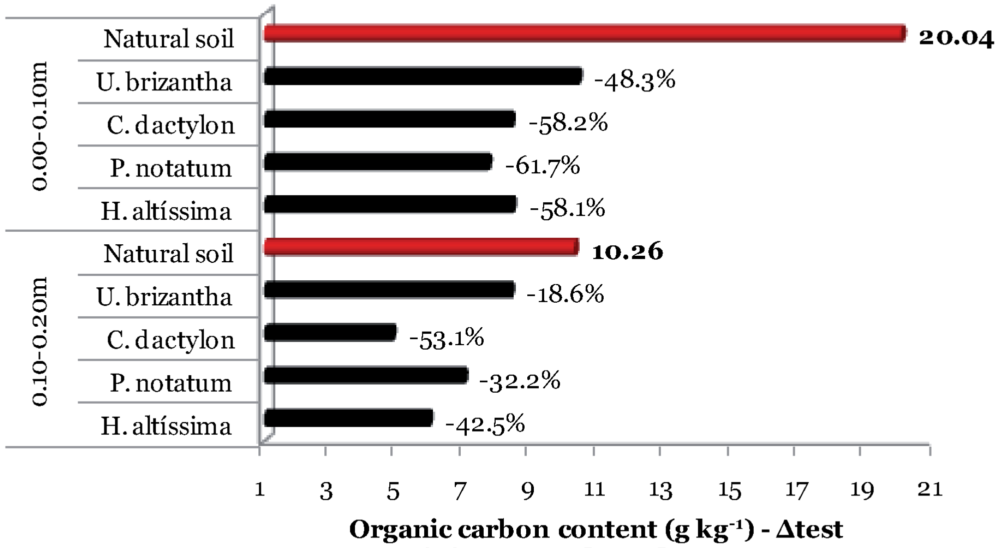

Figure 8.
Differences (Δtest) between the organic carbon content of minesoil after 8.6 years of revegetation (under perennial grasses) relative to the natural soil (under native vegetation).

However, in a minesoil in the USA, higher levels of organic carbon were observed in minesoils after 14 years (19.7 Mg ha^{-1}) and 26 years (13.4 Mg ha^{-1}) of revegetation than the natural soil (9.92 Mg ha^{-1}) [48].

The higher carbon content in natural soil is linked to the presence of microorganisms in the soil. In this sense, after 10.9 years of revegetation, it was observed that the natural soil presented 373 g kg^{-1}of microbial biomass carbon in the 0.00–0.10 m layer. The minesoil under the different grasses presented up to 42.69% lower values, except the soil under *Hemarthria altissima*, which presented values similar to the natural soil (**Figure 9a**). This result highlights the importance of adding carbon sources in recovering areas, aiming at the improvement of biochemical conditions, which may favor the return of soil biological balance.

On the other hand, **Figure 9b** shows that the metabolic quotient (qCO_2) values in the 0.00–0.10 m layer of the minesoil were 23.4 and 103.1% higher than the natural soil (0.64). A high qCO_2 indicates that the microbial population is experiencing

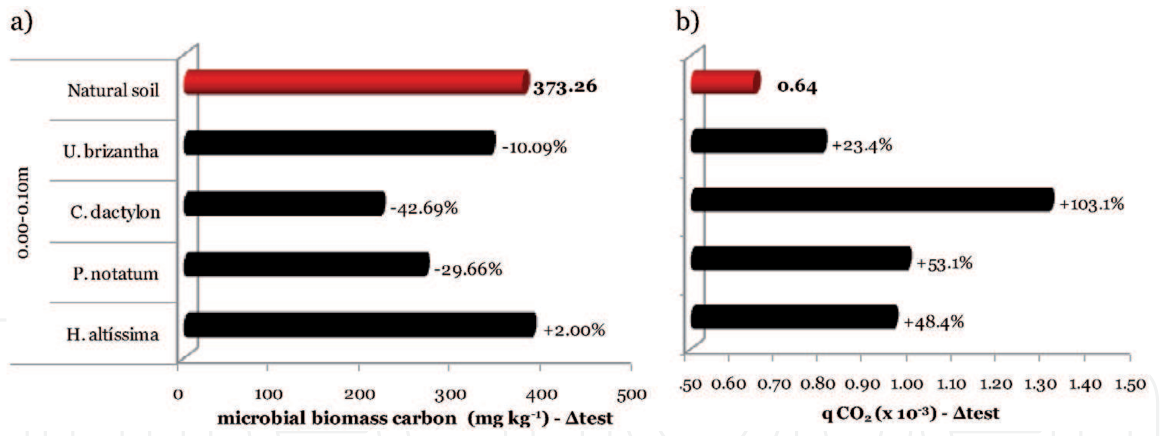

Figure 9.
Differences (Δtest) between microbial biomass carbon (a) and metabolic quotient (b) of minesoil after 10.9 years of revegetation (under perennial grasses) relative to natural soil (under native vegetation).

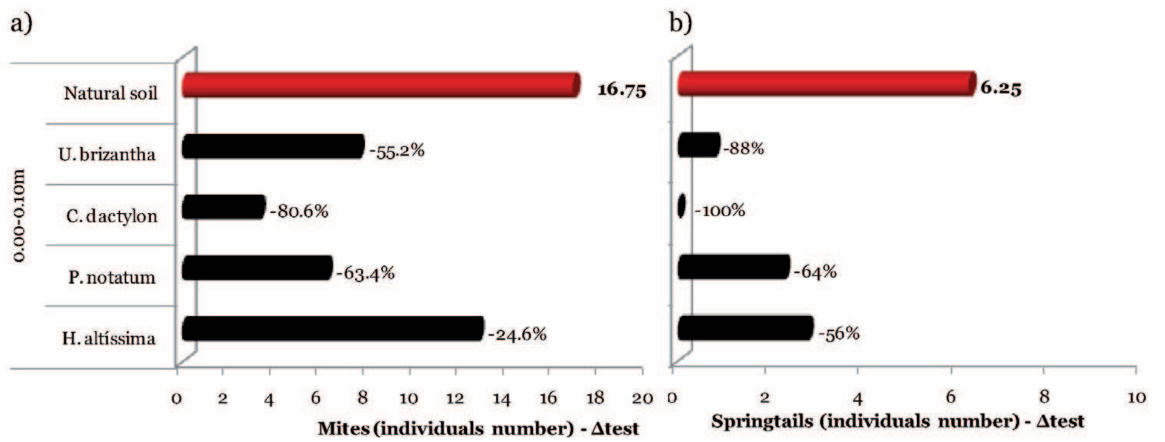

Figure 10.
Differences (Δtest) between the mites (a) and springtails population (b) of minesoil after 10.9 years of revegetation (under perennial grasses) relative to natural soil (under native vegetation).

high energy expenditure in maintaining it with greater respiration and CO_2 release rather than less carbon uptake into microbial cells.

Regarding the edaphic mesofauna, after 10.9 years of revegetation, the minesoil had a smaller mite population (between −24.6 and −80.6%) and a smaller springtail population (between −56 and −100%) compared to the reference soil. (**Figure 10a,b**), which was the consequence of the degraded state of the minesoil. On the other hand, it was observed that mites were larger than springtails population in both constructed minesoil and natural soil. This result is coherent because mites occur more in the interior of the soil, while the springtails occur on the surface [26].

According to the research results, it can be seen that the recovery of minesoils was more effective after 8.6 years of revegetation only in the physical condition up to 0.10 m depth. However, all the soil physical attributes and organic matter content are still far from the levels observed in the natural soil. The use of species with a more aggressive root system, such as the species selected in the present study (perennial grasses), possibly contributed to the positive results obtained in the short term, while it is expected that a following similar period (i.e., mid-term) is necessary for improvements in physical attributes below the 0.10 m layer.

About biological attributes, the 10.9 years of revegetation have not been sufficient yet to restore a mites and springtails population close to the natural soil.

4. Final considerations

Research results show that the reclaimed soils properties in coal mining areas, even after several years of reclamation, are still evolving and behind the quality of natural soils, especially the physical properties. This means that the reclaimed soil after mine decommissioning will be probably more fragile under cultivation than the natural soils, implying farmers to increase soils conservationist care in the first years. It is advisable that mining companies be aware of this and recommend farmers to cultivate the reclaimed soils using conservation systems, like no tillage systems, always maintaining straw covering on the soil's surface.

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Conflict of interest

The manuscript is original, has not been published before, and is not being considered for publication elsewhere in its final form neither in printed nor in electronic format and does not present any kind of conflict of interests. The publication has been approved by all coauthors as well as by the responsible authorities at the institute where the work has been carried out.

Author details

Luiz Fernando Spinelli Pinto[1], Lizete Stumpf[1]*, Pablo Miguel[1], Leonir Aldrighi Dutra Junior[2], Jeferson Diego Leidemer[2], Lucas da Silva Barbosa[2] and Mauricio Silva e Oliveira[1]

1 Agronomy College, Federal University of Pelotas, Brazil

2 Soil and Water Management and Conservation Program, Federal University of Pelotas, Brazil

*Address all correspondence to: zete.stumpf@gmail.com

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