Chapter

Impact of Revegetation on Ecological Restoration of a Constructed Soil in a Coal Mining in Southern Brazil

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Abstract

The main problems in the constructed soils are the generation of acid mine drainage promoted by the presence of coal debris in the overburden layer and the compaction of the topsoil promoted by the machine traffic when the material used in the overburden cover is more clayey. This book chapter aimed to show an overview of the impact of more than a decade of revegetation with different perennial grasses on the chemical, physical, and biological quality of constructed soil after coal mining. The study was carried out in a coal mining area, located in southern Brazil. The soil was constructed in early 2003 and the perennial grasses, *Hemarthria altissima*; *Paspalum notatum* cv. Pensacola; *Cynodon dactylon* cv Tifton; and *Urochloa brizantha;* were implanted in November/December 2003. In 11.5, 17.6 and 18 years of revegetation soil samples were collected and the chemical, physical, and biological attributes were determined. Our results show that liming is an important practice in the restoration of these strongly anthropized soils because this positively impacts the plants' development, facilitating the roots system expansion. Biological attributes such as soil fauna and the microorganism's population are the attributes that possibly takes longer to establish itself in these areas.

Keywords: *Hemarthria altissima*, *Paspalum notatum* cv. Pensacola, *Cynodon dactylon* cv Tifton, *Urochloa brizantha*

1. Introduction

Despite the great advancement of renewable energies in recent years, coal still plays an important role in the supply of electricity, as it has important reserves on all continents, contributing to the security of the energy matrix worldwide. It is estimated that in emerging markets by the year 2040, coal will supply 39% of the world's electricity [1]. In Brazil, the main coal reserve, called the Candiota Mine, is located in the state of Rio Grande do Sul, covering 38% of all national coal [2]. The process of coal extraction in the Candiota Mine occurs in the form of open-pit mining, which promotes intense impacts on the environment, such as the suppression of vegetation, soil, and rocks overlapping to ore. After coal extraction, the process of topographic recomposition of the area begins, which involves intense movement of heavy machinery aiming at filling the open pit by mining. Finally, the new soil profile in these areas presents, in general, two layers: a layer called overburden, composed of rock debris and eventually coal, and a layer of topsoil, composed of the mixture of horizons A, B, and C of the original soil. The main problems observed in the new profile of the constructed soil, which directly impact the revegetation of the mined areas, are the generation of acid mine drainage promoted by the presence of coal debris in the overburden layer and the compaction of the topsoil promoted by the machine traffic when the material used in the overburden cover is more clayey [3].

Acid mine drainage occurs when sulfite minerals, such as pyrite, are present in rock fragments used in topographic recomposition of the mined area [4]. Pyrite in contact with oxygen and water generates sulfuric acid [5], which drastically reduces pH [6], besides generating large concentrations of Fe, Mn, and Al in the solution [7], with negative implications in the revegetation of the degraded area [8]. Nunes [9] observed that construction methods that use low soil thickness originate from constructed soils with a large number of mining steriles and, consequently, with low pH values (around 2.4). Therefore, a greater thickness of topsoil over the overburden is critical during the construction of the new soil profile to minimize the occurrence of acid drainage. On the other hand, the improper handling and distribution of the topsoil can cause its compaction [10] and hinder the development of vegetation cover, the main starting point for the recovery of mined soils, since the accumulation of organic material results in positive changes in the physical–chemical properties of the new soil [11].

Revegetation is paramount in programs to recover degraded areas because the phytomass addition to the system provides a gradual increase in soil organic matter, which directly impacts microbiological activity and soil fauna diversity of these areas, promoting improvements in the ecological functions of the new ecosystem established after mining [12, 13]. In this sense, when evaluating the effect of revegetation on the microbiological attributes of soils impacted by mining, Longo et al. [14] found a significant increase in microbial biomass in open-pit mined areas after 3 years of legume revegetation. However, these were still below those found in forest soil (1344 and 1514 mg kg^{-1}, respectively). In India, when comparing constructed soils of different ages on forest species, Ahirwal et al. [15] also observed an increase in microbial biomass carbon over the years (5 years: 60 mg kg^{-1}; 7 years: 125 mg kg^{-1}; and 15 years: 270 mg kg^{-1}). Microbial biomass corresponds to about 80% of the living fraction of the soil, so it is considered an efficient indicator of the stage of degradation of soil, as it is directly related to the amount of organic matter added to the soil, in the form of live or dead plant residues, and participates strongly in soil formation processes, aggregation, cycling, and nutrient availability [16].

In relation to soil fauna, regardless of the revegetation used in the constructed soils, it has been observed population of mites and springtails predominance in these environments disturbed with different years of restoration [17–19]. On the other hand, in these soils strongly impacted by mining, even after a decade of revegetation, the populations of mites and springtails were still much lower than the populations observed in a natural soil without anthropic action [20]. The soil mesofauna represented by mites and springtails mainly plays an important role in the decomposition of plant residues, reducing the surface area of waste and facilitating the continuation of decomposition by microorganisms, especially bacteria [21]. As mites and springtails usually live in the soil pores closest to the surface, the physical changes that occur in the soil, such as compaction and consequently reduction of soil porosity, directly alter these populations [22]. On the other hand, pH changes also interfere in the diversity of these organisms because the presence or absence of some species may be related to the availability of specific ions in the soil solution. Therefore, soil management in order to improve fertility and decrease soil acidity can sometimes cause stress in these communities [23].

Therefore, the objective of this chapter was to analyze the impact of more than a decade of revegetation with different perennial grasses on the chemical, physical, and biological quality of constructed soil after coal mining in southern Brazil.

2. Materials and methods

The study was carried out in a coal mining area, under concession by Companhia Riograndense de Mineração (CRM), located in Candiota/RS with the following geographical coordinates: 31°33′56″S and 53°43′30″W (**Figure 1**). As described by Stumpf et al. [3], the soil was constructed in early 2003 and the experiment was installed in

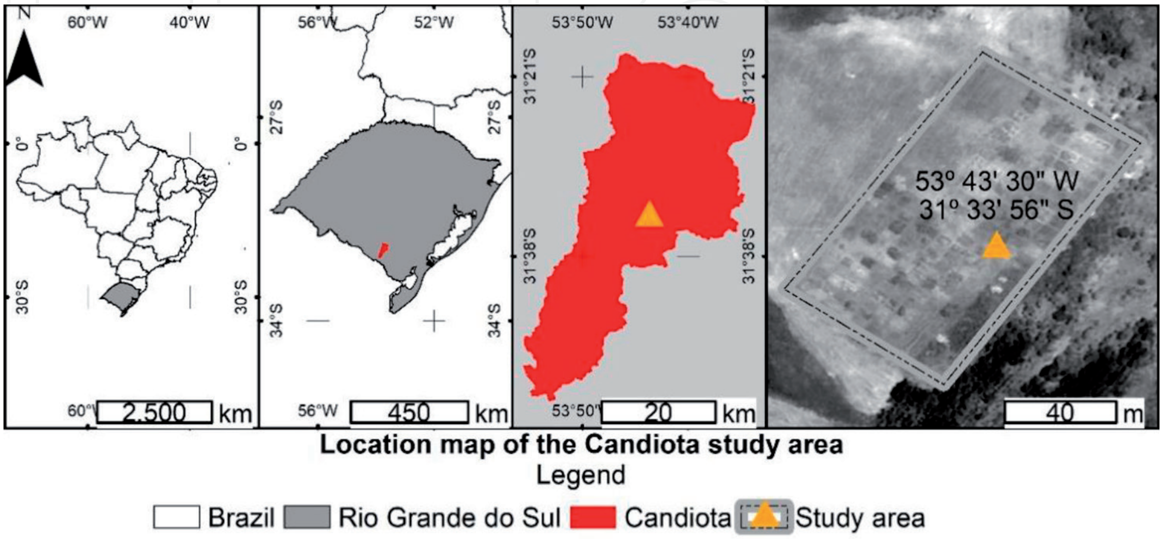

Figure 1.
Location map of Candiota study area.

November/December 2003 in plots of 20 m^2 (5 × 4 m) in a randomized block design with four replications. The soil layer replaced in the experimental area (Topsoil) comes from horizon B of the natural soil of the pre-mined area, a Rhodic Lixisol [24], as indicated by the clayey textural class, the dark red color (2.5 YR 3.5/6) and the low organic matter content (1.15%).

The perennial summer grasses, *Hemarthria altissima*; *Paspalum notatum* cv. Pensacola; *Cynodon dactylon* cv Tifton; and *Urochloa brizantha*, were implanted in November/December 2003. Before the implantation of plant species, the topsoil was scarified at a depth of 0.15 m, followed by a weight corresponding to 10.4 Mg ha^{-1} limestone with 100% PRNT and fertilization of 900 kg ha^{-1} of the formula Nitrogen, Phosphorus, Potassium 5-20-20 (NPK) based on results obtained by soil analysis. Annual fertilization in all plots was also performed annually by applying 250 kg ha^{-1} of the formula NPK 5-30-15 and 250 kg ha^{-1} of urea.

In March 2015 (11.5 years of revegetation), 16 soil samples were collected in the 0.00–0.10 m layer, with the aid of a cutting shovel, for the determination of chemical attributes: pH in water, calcium, magnesium, potassium, aluminum, and soil organic matter, and to determine the distribution of water-stable aggregates in different size classes.

Following the methodology of Tedesco et al. [25], the soil pH was determined in water at the ratio of 1:1 (soil:water); calcium (Ca^{+2}), magnesium (Mg^{+2}), and aluminum (Al^{+3}) exchangeable were extracted with KCl 1 mol L^{-1} and determined in the atomic absorption spectrophotometer (Ca^{+2} and Mg^{+2}) and by titration with NaOH (Al^{+3}). The available potassium content was estimated by the $Mehlich^{-1}$ method and analyzed by flame photometry. The potential acidity was extracted with calcium acetate and determined by titration with NaOH. Based on the results of the analyses, base and aluminum saturation was calculated. The soil carbon content was determined by the Walkley Black combustion method, in the fine earth fraction.

To determine the distribution of water-stable aggregates in different size classes, 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, when the soil was gently broken into large clods along the natural planes of weakness to obtain the natural aggregate, passed in a sieve with a mesh size of 9.52 mm, and then air-dried for two weeks. After that, four sub-samples were taken with approximately 50 g, one used to determine the moisture content and the other three were submitted to wet sieving with vertical following the method described by Kemper and Rosenau [26] and adapted by Palmeira et al. The intervals of aggregates classes were: C1: 9.52–4.76 mm; C2: 4.76–2.0 mm; C3: 2.00–1.00 mm; C4: 1.00–0.25 mm; C5: 0.25–0.105 mm, and C6:<0.105 mm. From these classes, the aggregates were separated into macroaggregates (>0.25 mm) and microaggregates (<0.25 mm), according to Tisdall and Oades [27].

In March 2015 (11.5 years of revegetation) and November 2021 (18 years of revegetation), 16 soil samples were collected in the 0.00–0.10 m layer, with the aid of a cutting shovel, to evaluate the microbiological attributes: microbial biomass carbon and basal respiration. The soil samples were preserved at refrigeration temperature (4°C) and for analysis of the microbial biomass were weighed 32 g of moist soil, in duplicate, where one repetition was subjected to irradiation in a microwave oven and another not, according to the methodology proposed by Islam and Weil [28]. The samples were titrated Fe2SO4 0.25 molc L^{-1} solution. Following the methodology described by Anderson and Domsch [29], basal respiration was performed using 100 g of fresh soil, with known moisture, and 20 mL of NaOH was added in hermetically sealed vials. After 21 days the solution was removed for titration with HCl.

In May 2021 (17.6 years of revegetation), 32 samples were collected using steel cylinders (0.050 m high and 0.047 m in diameter) to determine soil fauna organisms. The total number of individuals of the soil fauna was counted in 169.4 cm^3 of soil and the constructed soil moisture at the time of collection fluctuated between 25.2 and 31.8%. For the determination of soil fauna organisms, the Tullgren Extractor Funnel method proposed by Bachelier [30] was used. The samples were carefully placed in sieves with 2 mm mesh at the top of each funnel and, at the base of the hoppers, collector cups containing 70% alcohol and four drops of glycerin were placed in order to avoid rapid evaporation of alcohol. The samples were identified in each funnel and remained under the luminosity of lamps of 25 watts for 7 days, so that with the action of light and heat, the organisms move down, and thus be captured by the collector cup with a capacity of 50 ml. The soil fauna was identified and quantified at the class level according to Gallo et al. [31] with the aid of Opton magnifying glass, model TNE-10TN, with magnification ranging from 0.8 to 5×. The relative frequency of each group of organisms found in relation to the total number of organisms counted was calculated.

3. Results and discussion

Figure 2 shows the positive effects of limestone incorporation up to the approximate 0.15 m depth, which occurred before the implantation of plant species (Nov/Dec 2003). That is, even after 11.5 years of revegetation, the soil pH values in the 0.00–0.10 m layer (**Figure 2a**) are very close to or higher than the reference value for perennial grasses (pH > 5.5), according to the Soil Chemistry and Fertility Commission in the state of Rio Grande do Sul and Santa Catarina [32]. Consequently, base saturation is still at medium levels (65–80%) (**Figure 2b**), with high levels of calcium (>4 $cmol_c kg^{-1}$) and magnesium (>1 $cmol_c kg^{-1}$) (**Figure 2c** and **d** respectively), while aluminum saturation (**Figure 2e**) is below the level considered critical to plant development (<20%).

Although the chemical condition in the surface layer of the constructed soil is still adequate for the grasses development, the acidification effect, promoted by rainwater infiltration and annual fertilization with urea, is promoting soil pH and base saturation reductions if we consider the notes of Stumpf et al. [33]. According to the authors, at 8.6 years of revegetation, the surface layer of the constructed soil presented a pH between 5.74 and 6.25 (currently ranging from 5.40 and 5.70 – **Figure 2a**), while the base saturation was higher than 80% in all treatments (currently ranging from 61 to 69.50% – **Figure 2b**). Aluminum saturation also increased from values below 1.50% (at 8.6 years of revegetation) to values ranging from 3.20 to 15.33% when the revegetation was completed 11.5 years (**Figure 2e**). These results show, in the medium term, a new corrective action should be considered in the mined area so that aluminum saturation does not become restrictive to the root development of plants.

The chemical quality of constructed soils is essential to ensure the full plant's development in the long term, mainly to enable their root expansion, which is responsible for improving the physical quality of these soils [3, 11], which are strongly impacted by topsoil compaction. Da Silva Barboza et al. [34] noted that the first machine traffic event for the clay topsoil placement under the overburden promoted

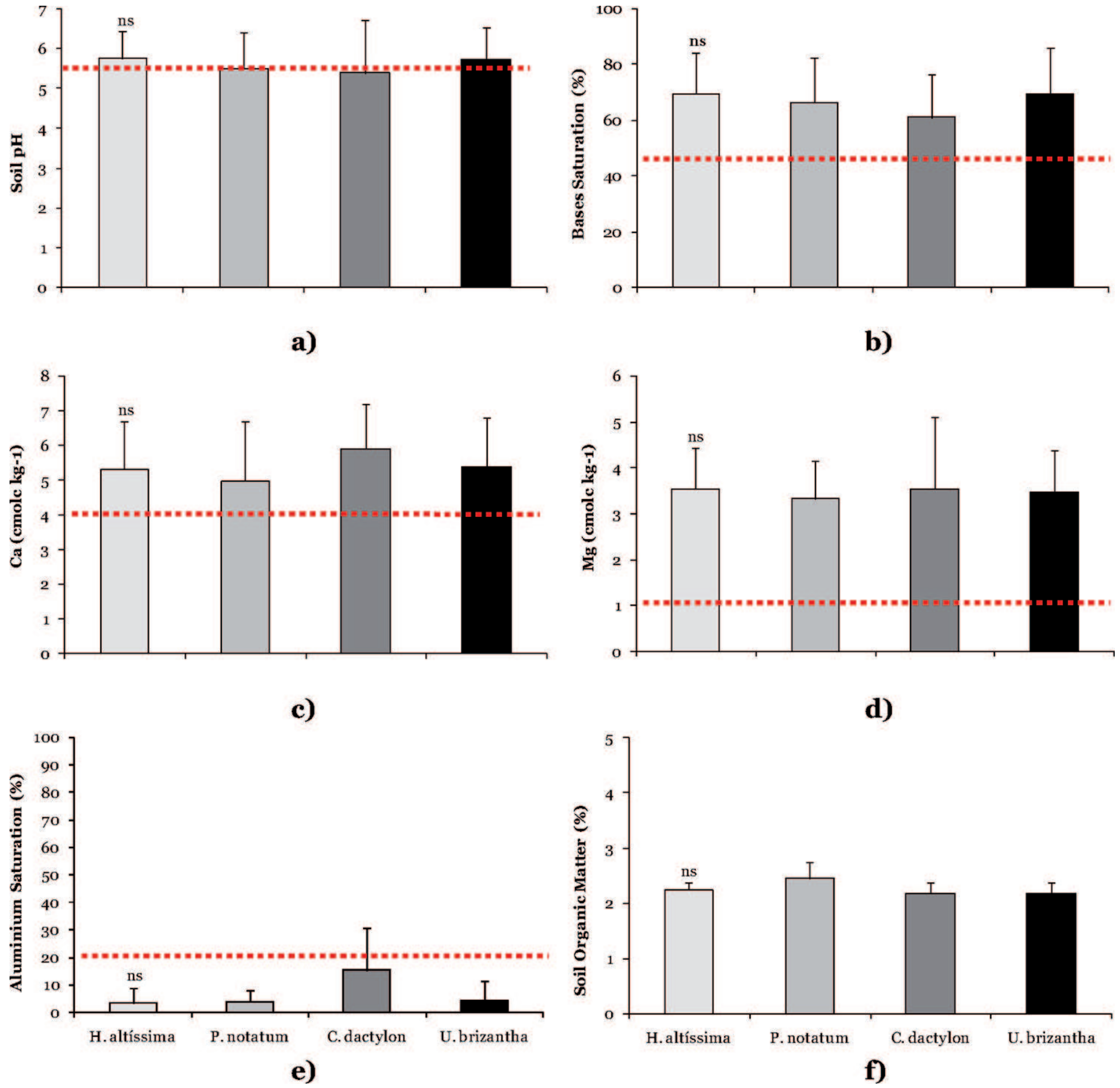

Figure 2.
Soil pH (a), base saturation (b), calcium (c) and magnesium contents (d), aluminum saturation (f), and organic matter content (e) in the 0.00–0.10 m layer of a constructed soil after coal mining and revegetated with perennial grasses for 11.5 years. Dashed red line indicates: (a) pH suitable for grass development; (b) base saturation considered low; (c) calcium and magnesium contents considered high (c, d respectively); (e) aluminum saturation considered limiting to root development; and (f) soil organic matter content considered low. Error bars mean standard deviation. Ns: Not significant to the Tuckey test ($p < 0.05$).

an increase in the bulk density of 23.5% in the 0.00–0.10 m layer in the minesoil newly formed. In addition, the soil particle's compression was evidenced after twelve machine traffic, with a significant increase in the percentage of soil macroaggregates from 22.56 (zero traffic event) to 36.58% (twelve traffic events). At the same time, it occurs a reduction in the percentage of microaggregates from 77.44 (zero traffic event) to 63.42% (twelve traffic events).

In our study, the descompaction effect of constructed soil through the root system grasses expansion can be evidenced by the similar proportion between the percentage of macro and microaggregates in the 0.00–0.10 m layer (**Figure 3**). That is, after 11.5 years of revegetation, the percentage of macroaggregates ranged between 52.60 and 58.86% (**Figure 3a**), while the percentage of microaggregates ranged between 41.13 and 47.41 (**Figure 3b**). This result is considered probably root effects, since at 8.6 years of revegetation this same layer of the constructed soil had a percentage of

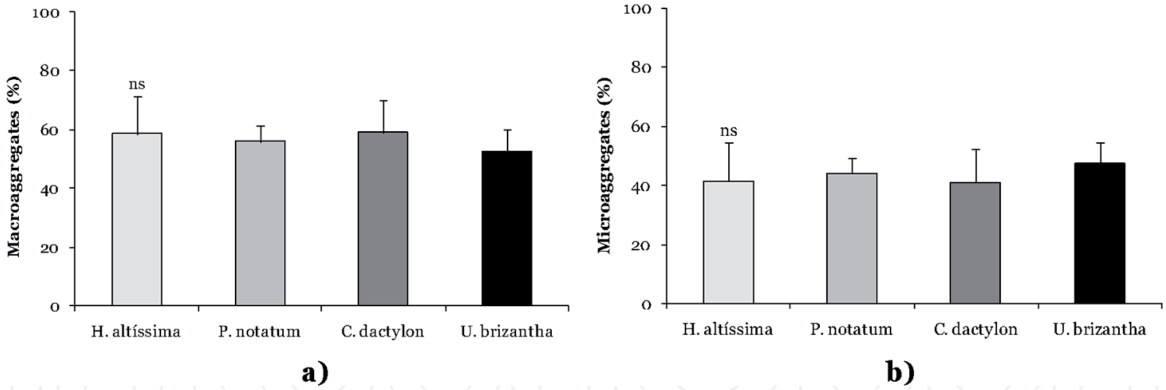

Figure 3.
Percentage of macroaggregates and microaggregates stable in water (a and b, respectively) in the 0.00–0.10 m layer of a constructed soil after coal mining and revegetated with perennial grasses for 11.5 years. Error bars mean standard deviation. Ns: Not significant to the Tuckey test ($p < 0.05$).

macroaggregates higher than 80%, while the percentage of microaggregates did not exceed 20%, according to Pinto et al. [35]. As the plants developed, the aggregates formed by compression were broken, increasing the presence of smaller aggregates, according to Stumpf et al. [3]. These results converge with Zhao et al. [11], which also observed improvement in the minesoil aggregation in the first 5–10 years of revegetation.

In addition to the improvements promoted by the grasses root system expansion, the phytomass deposition on the soil surface over the years also shows positive influence on soil biological attributes. Thus, **Figure 4a** shows that at 11.5 years of revegetation, microbial biomass was significantly higher in the soil under *Hemartria altissima* compared to *C. dactylon* cv. Tifton However, after 6.5 years of this evaluation, that is, after 18 years of revegetation, this difference promoted by grasses no longer exists. The microbial biomass indicates the carbon reserve potential of a soil [16], and its values may indicate the importance of vegetation cover in improving attributes related to soil biological quality.

Basal respiration, also known as microbial respiration, measures the amount of CO_2 released by microorganisms and is a parameter that, along with microbial biomass, is directly related to the amount of organic matter present in the soil. That is, the more organic material is added, the faster the "microbiological wheel" rotates, consuming more O_2, releasing nutrients and CO_2 from transformations, and producing more humus in the soil [16]. In this sense, at 11.5 years of revegetation, *H. altissima* and *U. brizantha* promoted the highest values of basal respiration in relation to others grasses. On the other hand, at 18 years of revegetation, only *U. brizantha* remained basal respiration superior to the other species (**Figure 4b**). This result may be a consequence of the high root exudation of this species, converging with the study by Stumpf et al. [3] who observed that *U. brizantha* had a root density of 13.29 Mg m^{-3} in the 0.00–0.10 m layer at 8.6 years of revegetation.

The evolution of basal respiration shows that there was a decrease of 10.7 to 49.8% of the values as the revegetation period progressed, regardless of the grass evaluated (**Figure 3b**). Possibly this may have occurred due to the fact that, after 18 years of revegetation, the accumulation of plant biomass on the soil surface caused microbial stress. That is, despite the high deposition of organic material in the soil, in general grasses have organic compounds of difficult degradation, requiring a range of more

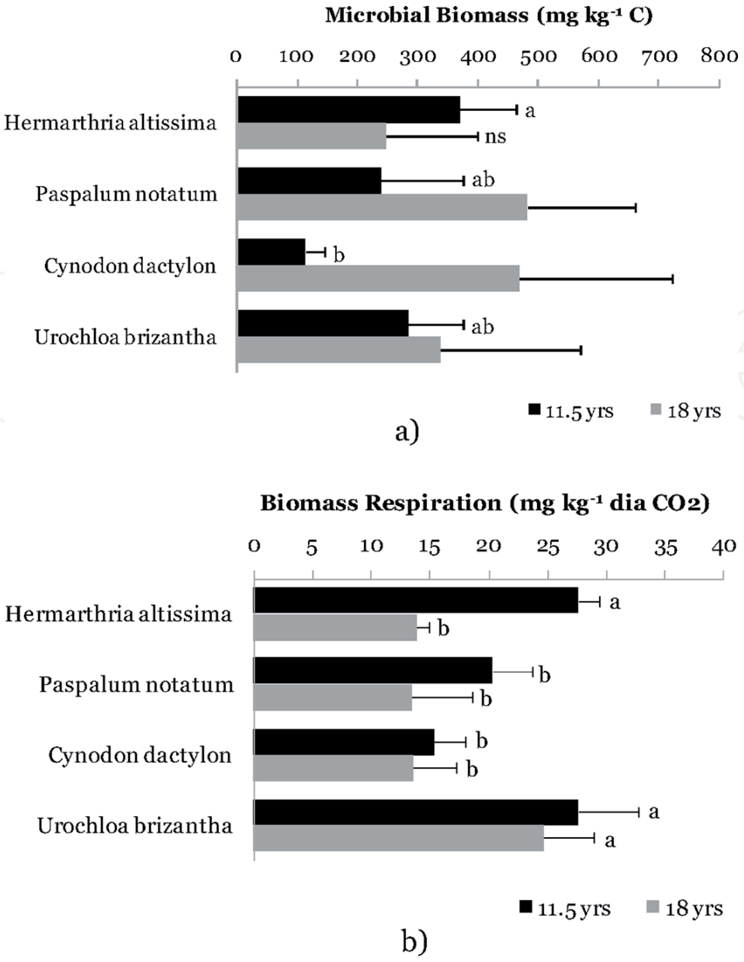

Figure 4.

Microbial biomass carbon (a) and basal respiration (b) of a constructed soil after 11.5 (black bars) and 18 years (gray bars) of revegetation with perennial grasses. Error bars mean standard deviation. Same letters in the black bars are not significantly different by the Tukey test ($p < 0.05$). Same letters in the gray bars are not significantly different by the Tukey test ($p < 0.05$).

specialized microorganisms for the decomposition of residues. Consequently, this also reflects on the low organic matter content of the constructed soil, which even after more than a decade of revegetation still has levels below 2.5% (**Figure 2f**).

Regarding the soil fauna of the constructed soil, at 17.6 years of revegetation, 1932 organisms were counted in 9 taxonomic groups in the four different perennial types of grass. The largest number of taxonomic groups (9) was observed in the soil under *C. dactylon* cv Tifton and under *U. brizantha*, followed by soil under *H. altissima* (8) *and P. notatum* cv Pensacola (7) (**Table 1**).

Mites were the most common soil fauna individuals among all taxonomic groups (RF% = 72.8), and when we analyzed the possible effect of each grass, we found that mites population in the constructed soil under *H. altissima* and *P. notatum* cv Pensacola was similar (281 and 289 individuals, respectively). However, in the constructed soil under *U. brizantha* there was a higher number of mites counted (478) compared to the other grasses, followed by *C. dactylon* cv Tifton (358) (**Table 1**). Possibly the largest number of mites in these grasses is due to the plant biomass quality deposited on the soil surface, contributing to a more favorable environment for these organisms. According to Urbanowski et al. [36], the increase in the mite population in the initial years of constructed soils restoration is due to the decomposition of organic matter; however, over the years, there may be a decrease in this population,

Soil fauna attributes	***Hemarthria altissima***	***Paspalum Notatum***	***Cynodon Dactylon***	***Urochloa Brizanta***	**RF (%)**
Mites	281	289	358	478	72.8
Springtails	86	69	148	110	21.4
Coleoptera	4	—	2	1	0.4
Dyptera	5	4	6	7	1.1
Dipluro	—	—	1	1	0.1
Enchytreid	1	4	1	4	0.5
Larva	3	3	11	3	1.0
Hymenoptera	6	18	5	1	1.5
Pupa	2	6	11	2	1.1

RF (%): Relative Frequence.

Table 1.
Total number of individuals of the edafica fauna of a constructed soil and revegetated with perennial grasses.

mainly affected by the type of organic material (litter) and not only by the amount of phytomass deposited on the soil surface.

Table 1 also observes that the second taxonomic group of the soil fauna most found were the springtails (RF% = 21.4) and the largest population was observed in the soil under *C. dactylon* cv Tifton (148), followed by the soil under *U. brizantha* (110). On the other hand, again, the grasses with the lowest number of individuals were *H. altissima* and *P. notatum* cv Pensacola (86 and 69, respectively). The springtails, along with the mites, are the organisms of greater abundance and diversity in the soil, considered the main indicators of soil fauna in constructed soils [17, 37]. Because they are the most representative groups of soil invertebrates, they control nutrient cycling through the predation of nematodes, protozoa, and fungi [38].

Among the other groups, which were numerically much lower than mites and springtails, the Hymenoptera group stands out, which obtained the third highest relative frequency in our study (RF% = 1.5) (**Table 1**). In descending order, the number of individuals in the different perennial grasses were: *P. notatum* cv Pensacola (18), *H. altissima* (6), *C. dactylon* cv Tifton (5), and *U. brizantha* (1). According to Rocha et al. [39], the richness of the Hymenoptera group tends to increase according to the complexity of the environments, and because it has a close relationship with vegetation, this group can be used as an indicator of degradation or alteration of the environment [40, 41]. Ants are fundamental soil organisms for soil "engineering processes" [42], they participate in the litter decomposition and incorporation in the soil, porosity maintenance and soil aggregates formation, community control, and microbial activities [43]. The predominance of mites, springtails, and hymenoptera groups observed in our study coincides with the study by Oliveira Filho et al. [19], who also observed areas in the process of recovery after coal mining, with different ages of restoration and revegetation, this same behavior.

4. Conclusion

This book chapter aimed to show an overview of the impact of more than a decade of revegetation with different perennial grasses on the chemical, physical, and biological quality of constructed soil after coal mining in southern Brazil. For the authors, it is clear that the liming is an important practice in the restoration of these strongly anthropized soils because this positively impacts the plant's development, facilitating the roots system expansion. Thus, the roots explore the constructed soil in search of nutrients and water, cracking the topsoil and improving its physical condition. On the other hand, biological attributes such as soil fauna and the microorganism's population are the attributes of the constructed soil that possibly takes longer to establish itself in these areas depending on the chemical and physical improvements of these areas, and it also depends on the phytomass quantity and quality added to the soil. Studies that monitor the evolution of the biological condition in these areas impacted by coal mining should be carried out in the long term always tied to the soil organic matter content for a better understanding of the actions of these organisms during the ecological recovery of these areas.

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