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Roots of Perennial Grasses in the Recovery of Soils Degraded by Coal Mining in Southern Brazil

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Abstract

Revegetation of degraded soils is crucial to prevent erosion and improve soil structure and quality. We aimed to elucidate the role of the root system of grasses on the reclamation of a soil constructed after coal mining. In Candiota city, in Brazil, perennial grasses (*Hemarthria*, *Paspalum*, *Cynodon*, and *Brizantha*) were cultivated for 103 months, when soil samples were collected from 0.00–0.30 m layer. The root development of these species substantially decreased in depth, reflecting soil restrictive conditions, as high soil penetration resistance, especially below 0.10 m, assigned to the use of heavy machinery during soil construction. Below 0.10 m depth, fine and flattened roots were observed, which penetrated through the cracks of compacted soil layers. Regardless of the soil layer, all plant species had a greater proportion of roots <0.49 than >0.50 mm diameter class, averaged 92 and 8%, respectively. Below 0.10 m depth, *Brizantha* increased the proportion of roots >0.50 mm diameter class, while the other grasses increased the proportion of roots <0.49 mm diameter class. The highest root density, volume, and length observed for *Brizantha* along the soil profile indicate its high potential to improve physical attributes and therefore the quality of the constructed soil.

Keywords: surface mining, soil compaction, soil penetration resistance, root growth, *Urochloa brizantha*

1. Introduction

According to the World Coal Association, the global coal reserves are approximately 860 billion tons, with a useful lifetime of approximately 109 years. These reserves are located

mainly in five countries, United States of America (USA), Russia, China, Australia, and India. Together, these countries possess 75% of the world's coal reserves. In Latin America, Brazil has one of the largest coal deposits [1], which are used to supply the following sectors: electric power (81.1%), paper and cellulose (4.9%), petrochemicals (3.3%), food production (2.9%), ceramics (2.6%), metallurgy and cement (1.3%), and others (2.7%) [2]. In Brazil, the greatest coal deposits are located in Rio Grande do Sul (RS) State, approximately 28.6 billion tons. The Candiota Mine in southwest of RS alone contains 38% of the national reserves [3]. Due to the shallow depth of the coal deposits in the Candiota Mine, which ranges from 10 to 25 m from the soil surface, it is exploited by opencast mining. First, the superficial soil horizons are removed and stored to be later used for the topographic recomposition of the area, covering the site previously mined. Thereafter, the rocks are removed to expose the coal deposits, which can be then exploited. Into the opened caves, the overburden (a mixture of rocks and discarded coal fragments) is deposited and leveled using tractors. Finally, the soil horizons, initially removed to expose the coal, are deposited on the surface of the soil under "construction," completing the topographic recomposition of the area and originating the so-called "constructed soil" or mine soil.

Constructed soils are young soils in terms of pedological processes and horizon development. These soils usually have high level of degradation and compaction as well as low levels of organic matter (OM), as a result of the mining and topographic recomposition of the landscape, as previously mentioned, dramatically hindering the reclamation of the area [4, 5]. Therefore, the utilization of the superficial soil horizons (topsoil), which concentrate OM and nutrients, to cover constructed soils followed by the revegetation of the area is crucial to accelerate the recovery of the soil quality [6]. However, it is important to mention that the irregular distribution of the topsoil material on the soil surface can aggravate the level of soil compaction [7], disfavoring the establishment of the cover crops used for revegetation, and increasing the vulnerability of the soil to erosion, hence retarding the reclamation of mine soils [8].

Due to the high perturbation of the ecosystem after surface mining activities and to the construction of a new soil profile, a time point "zero" of this soil with respect to soil development processes can be assumed. Within this scenario, the assessment and monitoring of the evolution of soil attributes is an extraordinary opportunity to improve our knowledge on the role of plant roots on the formation and stabilization of soil aggregates as well as on the accumulation and distribution of OM in the soil [9]. In the southeast of USA [10], similarities between the structure of a mine soil and that of a natural soil (unmined) were observed only after 23 years of reclamation.

In the southeast of Nigeria [11], higher bulk density was observed in a mine soil in comparison to that of a natural soil even after 30 years of revegetation. On the other hand, in the USA, the development of horizons of a constructed soil was observed in a relatively short time span of 10–15 years, with organic carbon accumulation, mainly within 0.00–0.10 m layer, after 5–10 years of soil reclamation [12]. In the north of China [8], the effect of the root system of cover crops on the formation of aggregates in the constructed soil was more pronounced after 5–10 years of revegetation. In a study carried out in Germany [13], it was verified that in the first four years of revegetation, the physical attributes of a constructed soil were still highly variable, and the authors recommended the implantation of perennial grasses with deep root system in the area in order to improve the soil structure more efficiently and rapidly.

In a previous work, we proposed a soil aggregation hierarchy for highly compacted constructed soils different from that hierarchy normally observed in unmined soils, as agricultural soils for example [14]. After coal mining in southern Brazil, the soil was revegetated with perennial grasses, and after 8.6 years of revegetation, we noticed first a root-induced disintegration of large cohesive aggregates formed by compression, followed by a re-aggregation process, with sequential formation and stabilization of the new aggregates. In this way, the interpretation of correlations between soil attributes usually observed for unmined soils cannot be, occasionally, directly transferred and applied to mine soils because they have different soil aggregation dynamics, at least at the beginning of soil revegetation. These findings reinforce the need and the opportunity to assume constructed soils as a new system, where monitoring of soil and plant attributes in the long term is a key to understand the formation of this new soil profile and moreover to anticipate strategies to improve soil quality [5].

The utilization of cover crops and the addition of OM to agricultural soils are known to promote the amelioration of soils poorly structured [15–17]. In this sense, special attention is given to grasses due to their high root density, which promotes the approximation of soil particles via water absorption along the soil profile, and therefore improves soil physical attributes. Additionally, root exudates increase the activity of soil microorganisms, consequently stimulating the aggregate formation and stabilization [18]. Hence, grasses have been considered indispensable plants in terms of soil preservation and reclamation [19].

Studies dedicated to investigate the root system development, its distribution, extension, and activity are extremely important to elucidate the effect of the plants, particularly the effect of the roots, on soil attributes, especially on attributes of unprotected and severely degraded soils, which are naturally more vulnerable to the intensification of the degradation processes. Despite the adverse plant growing conditions usually observed in constructed soils, especially in soils under early stage of reclamation, and the remarkable potential of grasses as regenerators of soil quality, few studies have been devoted to obtain direct measurements of root parameters of grasses in these soils [20].

This work is part of a long-term experiment that has been carried out for 15 years in Candiota, Brazil, to evaluate the potential of different grass species to improve the attributes of a soil constructed after surface coal mining. In our study, we focused to understand how the root system of the grasses develops and adapts when subjected to the severe soil compaction conditions of the constructed soil.

2. Methodology

The experimental site is located in Candiota city, in a coal mining area (31°33'56" S and 53°43'30" W), which is under concession of the Riograndense Mining Company. The soil was constructed in early 2003. The topsoil used to cover the overburden was composed mainly by the B horizon of the natural soil (prior to mining), a Rhodic Lixisol [21], with high clay content (466 g kg⁻¹ clay), dark red color (2.5 YR 3/6), and lower OM content (12 g kg⁻¹) compared to the A horizon (21 g kg⁻¹). The main steps of the coal extraction and soil construction were: (I) removal of A, B, and C horizons of the Rhodic Lixisol; (II) removal of saprolite and overburden

with a dragline excavator; (III) coal extraction; (IV) filling of the caves with overburden spoils and leveling of these piles with heavy machinery aiming the topographic recomposition of the area; and (V) distribution of the topsoil (separated in step I) on the surface of the constructed soil. Illustration of the process of soil construction in Candiota was earlier reported [22].

The experiment was installed in November/December 2003 in a randomized block design with four replicates (each plot with $4 \text{ m} \times 5 \text{ m} = 20 \text{ m}^2$). Types of grasses and planting materials used as treatments consisted of perennial summer grasses: *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}). Due to the severe soil compaction caused by the intense use of heavy machinery during the soil construction, 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.

The root sampling was performed in July 2012, 103 months after the implantation of the grasses. Roots were sampled by the monolith method [23] using a nail board (0.40 m length \times 0.30 m height \times 0.035 m wide), where the nails were set at equidistant positions of 0.05 m on the board. One monolith per plot was collected, totalizing 16 nail boards (four replicates per treatment). The monoliths were packed with plastic film and taken to the laboratory for washing and root separation. The washing consisted of soaking the plate for 24 h in a 0.2 M NaOH solution for soil dispersing and to facilitate the cleaning of the roots. Hereafter, they were washed in running water or with water jets to remove soil particles from the board. The nails allowed adequate fixation of the roots on the plate at the time of washing. In order to assure the fixation, one metal mesh at the bottom and other in front of the plate were used. After washing, the roots along the monolith were stratified in three layers, 0.00–0.10, 0.10–0.20, and 0.20–0.30 m, cut and washed on a 1 mm mesh sieve, stored in plastic bags, and refrigerated at 2°C temperature. The roots were scanned on an HP Scanjet 3570C scanner, and the software SAFIRA [24] was used to analyze the images and to obtain root volume (RV), root length (RL), root area (RA), and mean root diameter (MRD). After scanning, the roots were oven-dried at 65°C for 72 h, and the root dry mass (RDM) was determined. The root density (RD) of each layer was calculated by the ratio of RDM to the respective soil volume occupied by the root.

The soil mechanical penetration resistance (PR) was measured at the time of the root sampling at 48 points of the experimental area. The PR was evaluated up to 0.30 soil depth using an impact penetrometer [25].

3. Results and discussion

The qualitative evaluation of the root system of the cover crops was performed based on the monoliths showed in **Figures 1–4**. The monoliths allowed to observe overburden layers in some of the replicates, generally below 0.20 m depth, as shown in monoliths III and IV (*Hemarthria altissima* and *Cynodon dactylon*), monolith I (*Paspalum notatum*), and monoliths I

and IV (*Urochloa brizantha*). The variability of the overburden layer thickness reflects the heterogeneous distribution of the topsoil material on the overburden surface at the time of the soil construction, as earlier discussed [5].

Although overburden layers were evidenced within 0.15–0.20 m soil layer, apparently they did not limit root development to 0.20–0.30 m layer, since roots of some plant species were observed at this depth. However, it is relevant to highlight that the presence of overburden becomes problematic if associated with pyrite, which is responsible for acid drainage processes that are potentially harmful to the environment. From the plant survival perspective, the deep root growth is beneficial in terms of plant water use strategies and anchoring, but from the environmental point of view, if the roots reach an overburden plus pyrite layer, they can intensify the sulfurization process, once the macro porous created by the roots increase the water infiltration into the soil and the migration of oxygen to subsurface layers [26].

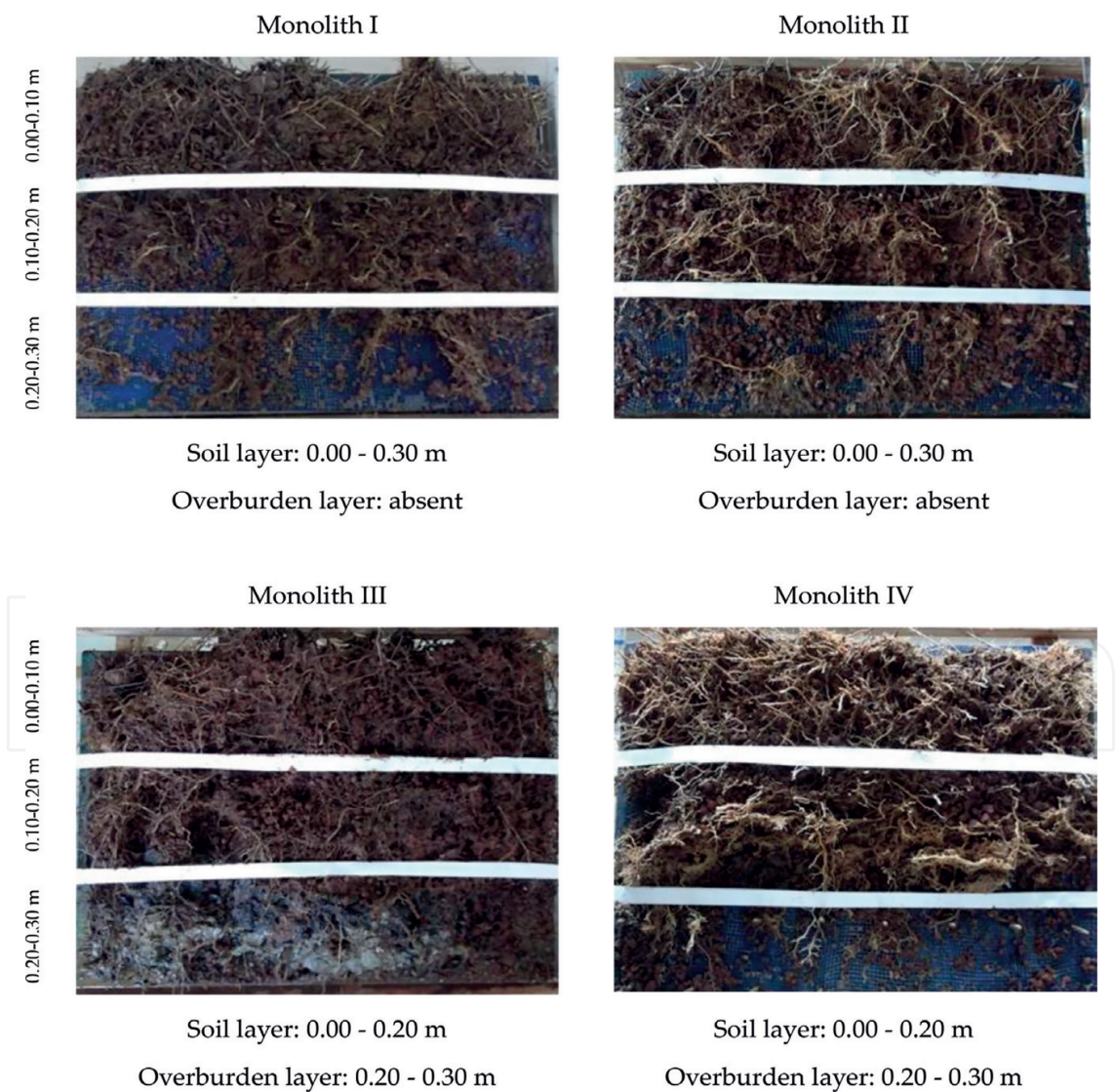


Figure 1. Qualitative evaluation of *Hemarthria altissima* roots after washing of the soil monoliths and soil/overburden distribution within 0.00–0.30 m layer.

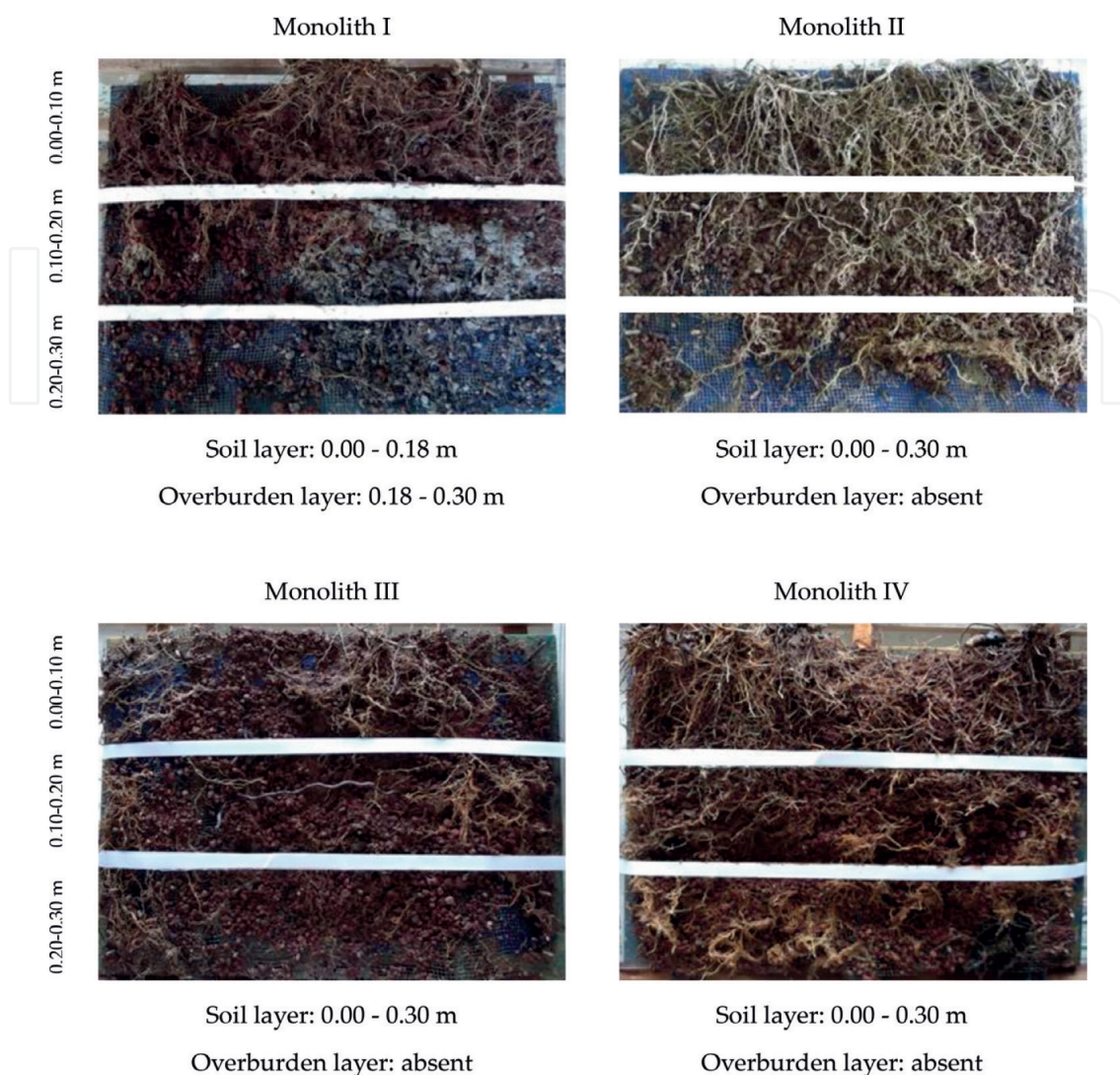


Figure 2. Qualitative evaluation of *Paspalum notatum* cv. Pensacola roots after washing of the soil monoliths and soil/overburden distribution within 0.00–0.30 m layer.

The depth of rooting is a valuable indicator of the root system quality [27]. In our study, we observed that the four plant species were able to develop roots up to 0.30 m depth, but most of the roots were concentrated at 0.00–0.10 m layer (**Table 1**). Overall, the proportion of the root system of *Hemarthria altissima*, *Cynodon dactylon*, and *Urochloa brizantha* substantially decreased from 0.10–0.20 to 0.20–0.30 m layer. Interestingly, the root system of *Paspalum notatum* behaved differently from the other species and developed more uniformly within 0.10–0.30 m layer as evidenced by the RD, RV, RL, and RA proportions along the soil profile (**Table 1**). These findings indicate the ability of this species to establish its root system along the soil profile (0.00–0.30 m) even though the overburden layer and the higher PR observed near to 0.20 m depth in this treatment (**Figures 2** and **5**) could have hindered the root system deepening.

In general, approximately 44 and 75% of the root mass of grasses develops at 0.00–0.10 and 0.00–0.30 m layer, respectively [28]. Similar data have also been observed for the root growth of an annual grass (*Bromus tectorum*) and a perennial grass (*Agropyron desertorum*), and nearly

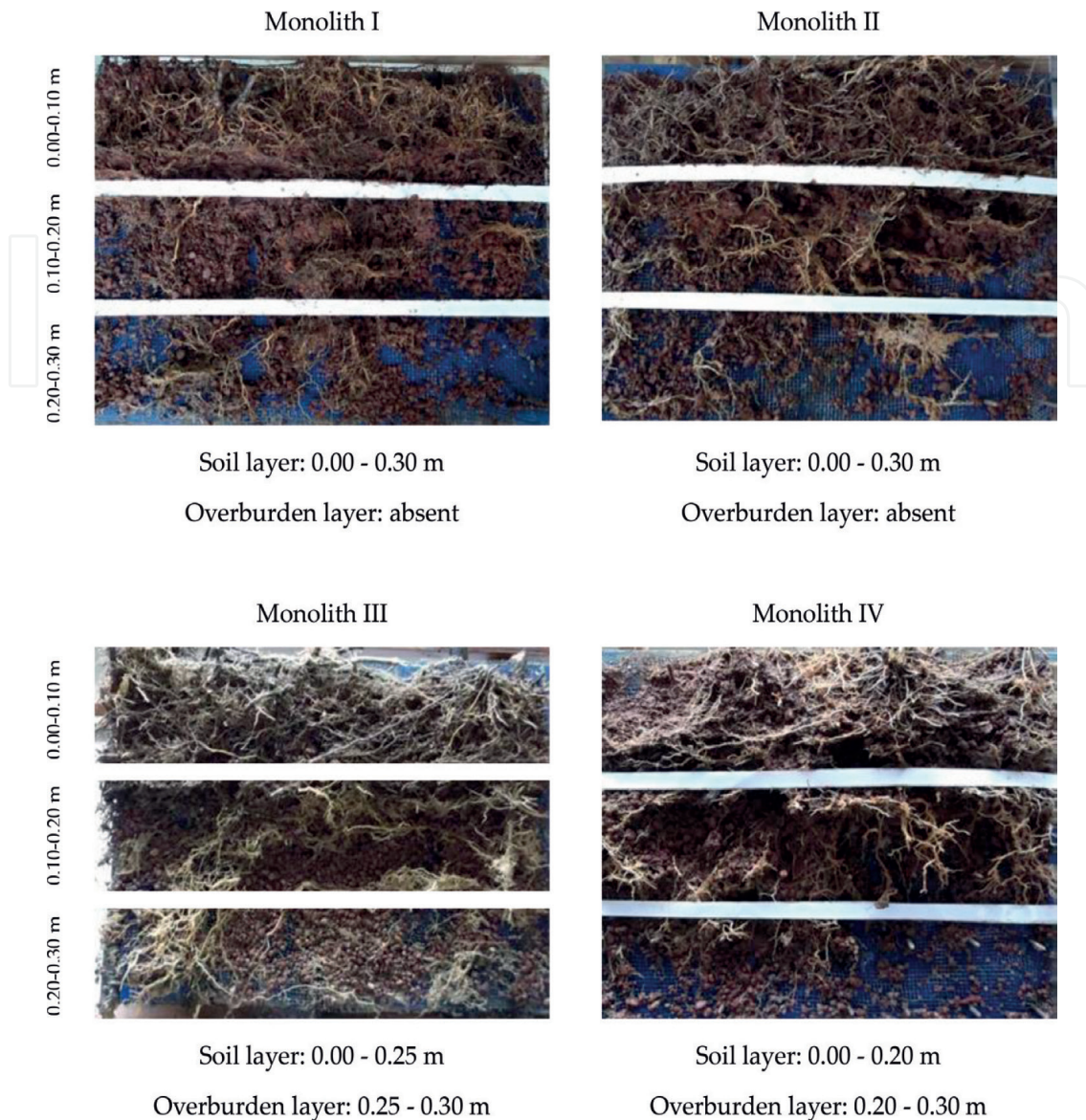


Figure 3. Qualitative evaluation of *Cynodon dactylon* cv. Tifton roots after washing of the soil monoliths and soil/overburden distribution within 0.00–0.30 m layer.

75% of the root biomass was distributed within the first 0.30 m depth [29]. In our study, the concentration of roots at 0.00–0.10 m layer was substantially higher than those reported earlier. The proportion of root parameters for the four grasses for the upper 0.10 m ranged from 62 to 68% for RD, from 54 to 63% for RV, from 52 to 61% for RL, and from 53 to 61% for RA (Table 1). Around 95% of the plant species develop a deeper root system in sandy soils than in clayey soils [30]. Considering that the clay content of the constructed soil is considerably high along the soil profile (453 g kg⁻¹ at 0.00–0.10 m, 478 g kg⁻¹ at 0.10–0.20 m, and 467 g kg⁻¹ at 0.20–0.30 m), it may explain the shallower root system of the grasses observed in our experiment when compared to that of other authors. In addition, high RD values are commonly associated to the development of plants under suboptimal growing conditions [31], such as that of high PR found in our soil, especially below 0.10 m depth (Figure 5). The roots of most of the plant species can hardly grow in deep soil depths subjected to high compaction levels [32],

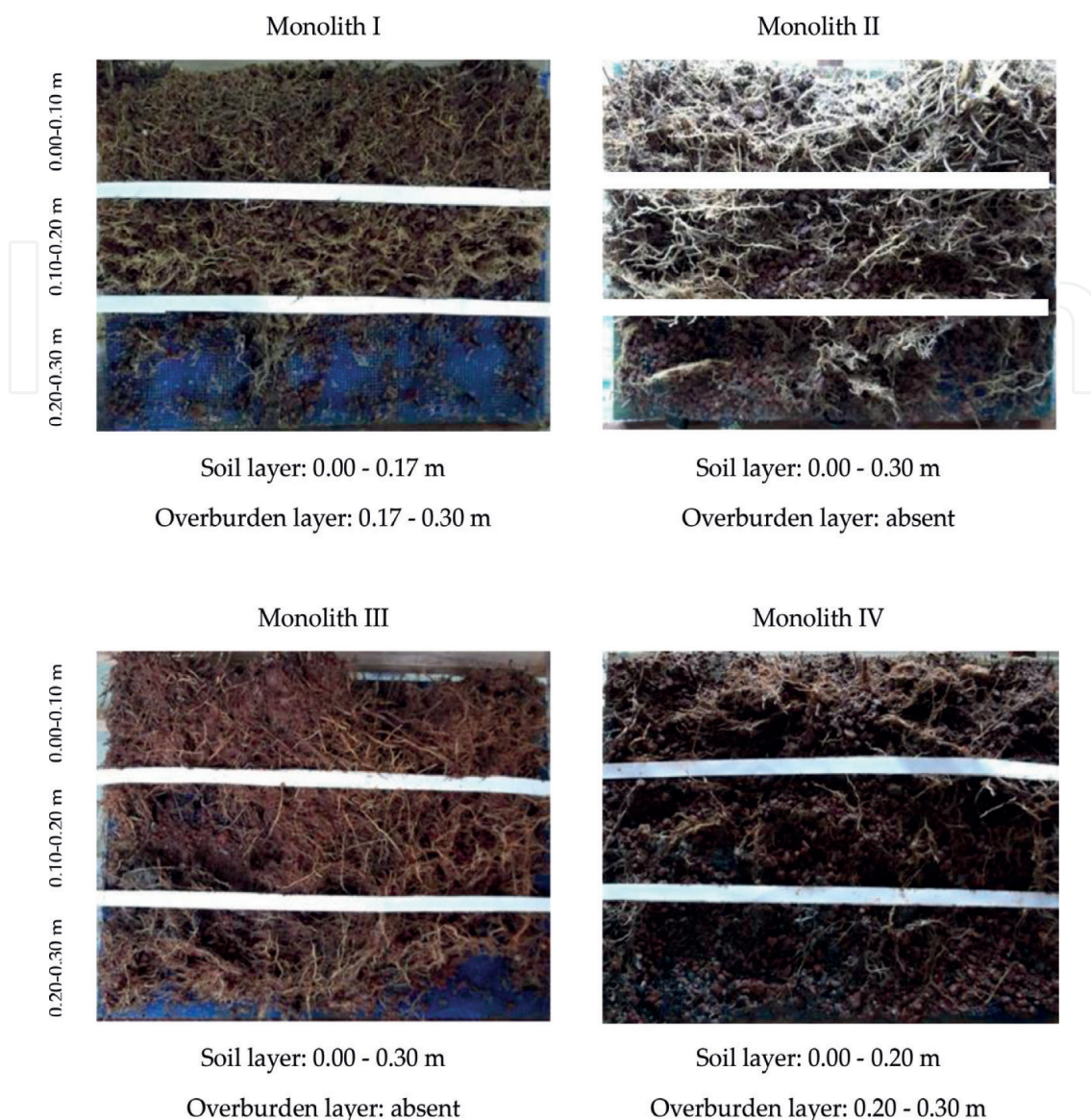


Figure 4. Qualitative evaluation of *Urochloa brizantha* roots after washing of the soil monoliths and soil/overburden distribution within 0.00–0.30 m layer.

and thus these plants become more susceptible when subjected to extreme climatic events. In agricultural soils, this problem has been reported repeatedly, such as greater concentration of roots of cereals (*Eleusine coracana* and *Pennisetum americanum*) observed near the surface of a clayey soil due to the compaction of the subsurface soil layers [33]. These findings corroborate authors that reported the concentration of maize roots (*Zea mays*) within 0.00–0.07 m layer (64%) of an Oxisol [34]. The results were assigned to the physical degradation of the subsurface soil layers, which limited root movement to the lower soil layer.

The main reason for the root thickening in different plant species is related to soil compaction. Deformed and flattened roots [20] as well as thick roots and the concentration of roots near to the soil surface [17] were reported in agricultural soils with compaction problems. In our study, greater proportion of the root system biomass of the grasses, independently on the

Grasses	Layer	% Layer ¹			
		RD	RV	RL	RA
<i>Hemarthria altissima</i>	0.00–0.10 m	67.82	62.77	58.79	60.74
	0.10–0.20 m	25.29	27.59	28.67	28.12
	0.20–0.30 m	6.89	9.64	12.54	11.14
<i>Paspalum notatum</i>	0.00–0.10 m	62.44	63.25	60.99	62.98
	0.10–0.20 m	19.45	17.83	19.49	18.12
	0.20–0.30 m	18.11	18.92	19.52	18.90
<i>Cynodon dactylon</i>	0.00–0.10 m	61.98	53.73	51.84	53.28
	0.10–0.20 m	29.25	36.59	33.08	34.47
	0.20–0.30 m	8.77	9.68	15.08	12.26
<i>Urochloa brizantha</i>	0.00–0.10 m	64.72	60.91	60.12	60.42
	0.10–0.20 m	29.24	32.56	31.59	32.14
	0.20–0.30 m	6.04	6.53	8.29	7.44

Table 1. Proportion of root density (RD), root volume (RV), root length (RL), and root area (RA) values of four perennial grasses distributed at 0.00–0.10, 0.10–0.20 m, and 0.20–0.30 m layers of a constructed soil after 103 months of revegetation.

soil layer, was composed of fine roots (<0.49 mm diameter class) (**Table 2**). Grasses preferably invest in fine roots, but the residence time of the roots in the soil depends on the environmental conditions and on the plant species [35]. In this way, we observed that as *Hemarthria altissima*, *Paspalum notatum*, and *Cynodon dactylon* deepen their root system they proportionally invested more in roots <0.49 mm diameter class, while *Urochloa brizantha* proportionally decreased roots within this same diameter class and slightly invest more in thicker roots (**Table 2**).

The proportion of roots >0.50 mm diameter class was equal or lower than 10% in all plant species, regardless the soil layer (**Table 2**). Nevertheless, the proportion of roots within this diameter class along the soil profile increased in *Urochloa brizantha* and decreased in *Hemarthria altissima*, *Paspalum notatum*, and *Cynodon dactylon* (**Table 2**).

With respect to the color of the roots, white roots are classified as active, brown roots as senescent and darkened roots as dead [36]. Overall, we observed predominance of brown roots at 0.00–0.10 m layer, a balance between brown and white roots at 0.10–0.20 m layer, and predominance of white roots at 0.20–0.30 m layer, indicating that the plants were able to surpass the highly compacted soil layers, especially at 0.20 m (**Figure 5**) and are actively exploring the soil below 0.20 m.

In general, the highest RDM, RV, and RL values were noticed in *Urochloa brizantha*, mainly within 0.00–0.20 m layer, while the lowest values were observed in *Paspalum notatum*. Below 0.20 m, differences between the grasses were less pronounced (**Figure 6a–c**). The inherent vigorous root system of *Urochloa brizantha* together with its great adaptation to the constructed

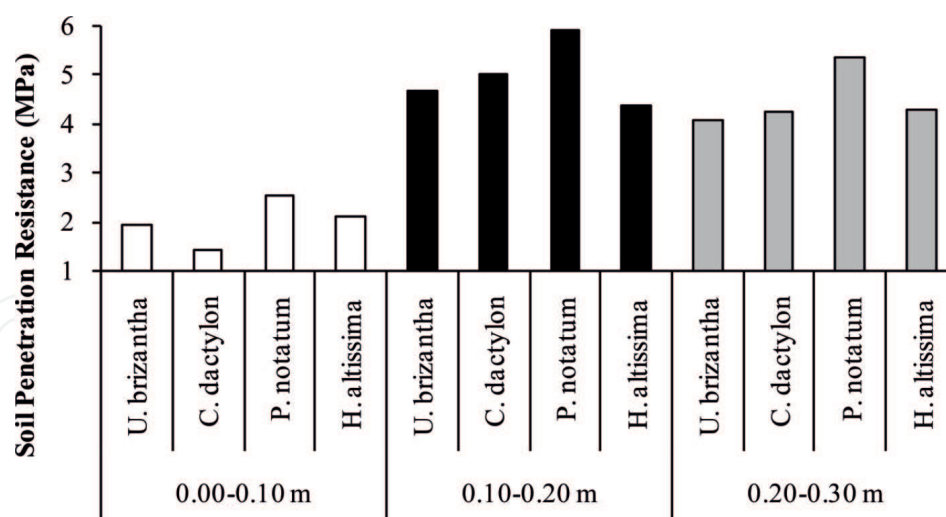


Figure 5. Soil penetration resistance at 0.00–0.10, 0.10–0.20 m, and 0.20–0.30 m layers of a constructed soil after 103 months of revegetation with four perennial grasses.

soil as observed in the present study may have boosted the potential of this species to promote the amelioration of soil physical attributes as reported in a previous work [37].

The roots tend to occupy very low proportions of the soil volume, less than 1% of the arable layer [38]. At 0.00–0.20 m layer, the soil volume occupied by the roots of the grasses decreased

Grasses	Layer	% of roots in diameter classes	
		<0.49 mm	>0.50 mm
<i>Hemarthria altissima</i>	0.00–0.10 m	90.93	9.07
	0.10–0.20 m	91.22	8.78
	0.20–0.30 m	93.51	6.49
<i>Paspalum notatum</i>	0.00–0.10 m	90.11	9.89
	0.10–0.20 m	91.01	8.99
	0.20–0.30 m	92.32	7.68
<i>Cynodon dactylon</i>	0.00–0.10 m	91.87	8.13
	0.10–0.20 m	92.24	7.76
	0.20–0.30 m	96.01	3.99
<i>Urochloa brizantha</i>	0.00–0.10 m	93.23	6.77
	0.10–0.20 m	89.99	10.01
	0.20–0.30 m	89.60	10.40

Table 2. Perennial grass roots distribution in diameter classes at 0.00–0.10, 0.10–0.20 m, and 0.20–0.30 m layers of a constructed soil after 103 months of revegetation.

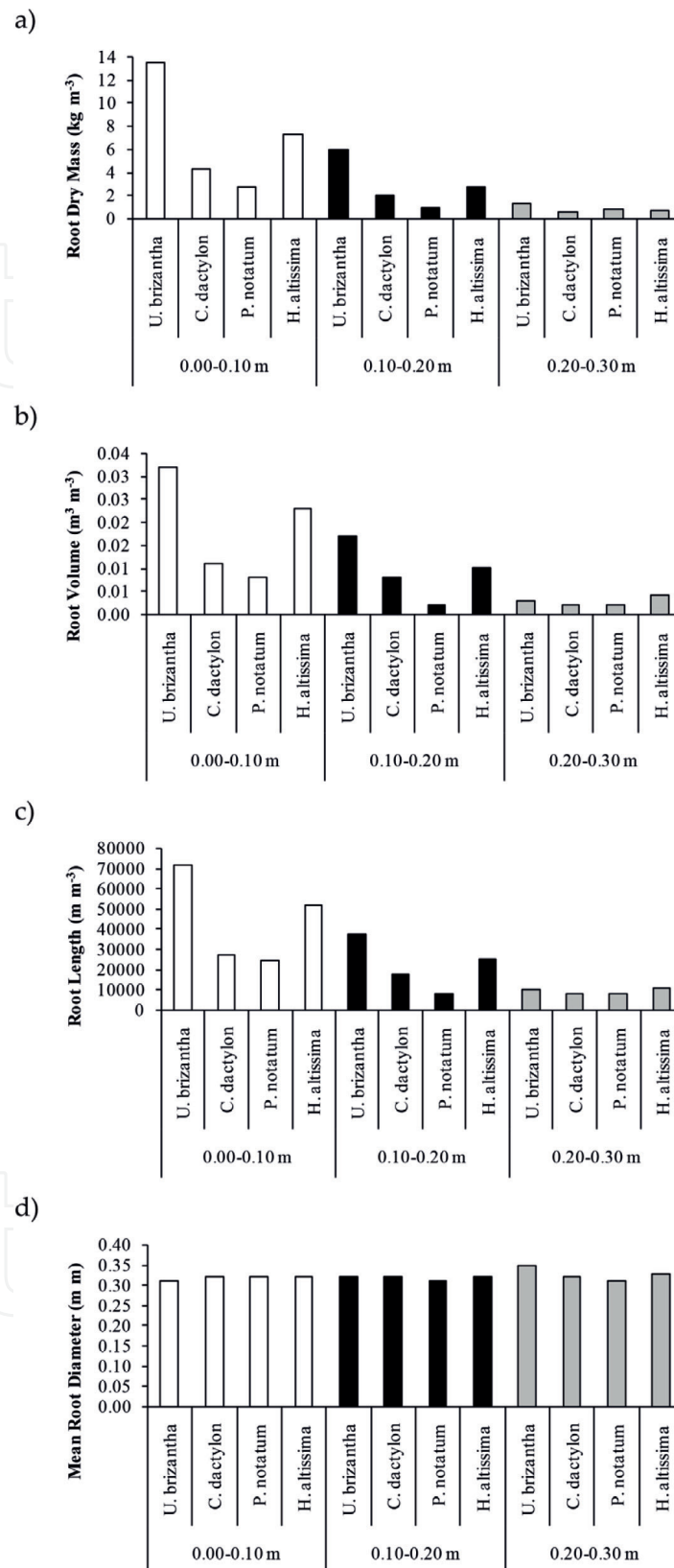


Figure 6. Root dry mass (a), root volume (b), root length (c), and root diameter (d) of four perennial grasses at 0.00–0.10, 0.10–0.20, and 0.20–0.30 m depth of a constructed soil after 103 months of revegetation.

as follows: *Urochloa brizantha*, 2.45%; *Hemarthria altissima*, 1.65%; *Cynodon dactylon*, 0.95%; and *Paspalum notatum*, 0.50% (**Figure 6b**). Additionally, it is important to give attention to the high RV of *Urochloa brizantha* at 0.00–0.10 m layer, 3.2%.

Combining the data of **Figures 5 and 6**, the effect of the soil PR on the roots of the grasses can be highlighted as:

- a. *Hemarthria altissima*—when PR increased 107%, from 2.12 to 4.39 MPa, RV and RL were decreased by 56.5 and 51.2%, respectively;
- b. *Paspalum notatum*—when PR increased 135%, from 2.52 MPa to 5.92 MPa, RV and RL were decreased by 75.0 and 68.0%, respectively;
- c. *Cynodon dactylon*—when PR increased 256%, from 1.41 to 5.04 MPa, RV and RL were decreased by 27.3 and 36.2%, respectively;
- d. *Urochloa brizantha* - when PR increased 143%, from 1.92 to 4.66 MPa, RV and RL were decreased by 46.9 and 47.5%, respectively.

The data above reveal the ability of *Cynodon dactylon* to tolerate highly compacted soil conditions. At the same time that this species was subjected to the highest proportional increase in PR, it was less sensible than the other species with regard to RV and RL. However, the PR below 0.10 m depth is expected to decrease more consistently over time, as the roots disrupt the compacted layer, similarly to what is observed in agricultural soils under conservation tillage systems, for example, no tillage [39].

Similar MRD was observed for all grasses, ranging from 0.31 to 035 mm (**Figure 6d**). However, along the soil profile, the MRD of the plant species behaved differently. The MRD of *Hemarthria altissima* and particularly that of *Urochloa brizantha* increased in depth, while the MRD of *Cynodon dactylon* and *Paspalum notatum* was constant or decreased along the soil profile, respectively (**Figure 6d**). Although the root thickening is generally associated to unfavorable soil compaction conditions, at the same time, it indicates the adaptation of *Urochloa brizantha* and *Hemarthria altissima* to the dramatic conditions of the constructed soil. In fact, the RV, RL, and RDM values of these species were superior than that of the other species, not only near to the soil surface where growing conditions are more reasonable, but also below 0.10 m depth in general (**Figure 6a–c**). In this way, we can expect that the soil physical attributes of subsurface soil layers will be improved more rapidly by *Hemarthria altissima* and *Urochloa brizantha* than by *Paspalum notatum* and *Cynodon dactylon*.

4. Conclusions

After surface coal mining, construction of the soil and its revegetation with perennial grasses for 103 months, we conclude that:

1. The root system of all grasses was markedly concentrated within 0.00–0.10 m layer, most probably due to impeditive physical conditions of the soil below 0.10 m.

2. The qualitative analysis of the soil monoliths evidenced that the plants explored the soil below 0.10 m depth via fine and flattened roots mainly, which penetrated through the cracks of the compacted soil layer.
3. Regardless the soil layer, the roots of all grass species were predominantly <0.49 mm diameter class, classified as very fine roots. However, below 0.10 m depth, *Urochloa brizantha* increased the proportion of roots >0.50 mm diameter class, while *Hemarthria altissima*, *Paspalum notatum*, and *Cynodon dactylon* rather increased the proportion of roots <0.49 mm diameter class.
4. The root system of *Urochloa brizantha* developed more consistently along the soil profile compared to the other species, indicating the greater potential of this species to surpass compacted layers and moreover to improve soil physical attributes not only above 0.10 m but also below 0.10 m as well, where soil conditions are more critical.
5. Once the roots of the plant species tested in this work can potentially reach deep depths and overburden layers, the recommendation of these species to the reclamation of soils constructed after coal mining should consider the thickness of the topsoil used to cover the overburden and the presence of pyrite in order to avoid acid drainage.

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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.

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