

Chapter

Evolution of a Technosol Cultivated with Perennial Grass, over 15 Years: Potential Use as Carbon Sinks

Luís Eduardo Torma Burgueño, Luiz Fernando Spinelli Pinto, Lizete Stumpf, Clause Fátima de Brum Piana, Maurício Silva de Oliveira, Maurizio Silveira Quadro and Pablo Miguel

Abstract

In this study, we investigated the increase in carbon in the surface layer of a technosol, promoted by perennial grasses, and its implications for the recovery of land degraded by coal mining in southern Brazil, and its potential as carbon sinks. To monitor the recovery process of soils constructed after coal mining, a randomized block experiment was implemented in 2003, with several species of perennial grasses, in a coal mine in southern Brazil. Over 15 years of monitoring, the species *Hemarthria altissima* and *Urochloa brizantha* showed the best rates of incorporation of organic matter and soil decompaction capacity. To evaluate the efficiency of these species over time in recovering these technosols, polynomial regression models were adjusted to total organic carbon (TOC) and soil bulk density (Bd) data. The ability of these species to increase organic soil carbon stocks (SCS) was also estimated. The results verified showed that the use of perennial grasses in the recovery processes of these areas can, over time, promote an increase in TOC (425%) and reduce Bd. In this sense, it is believed that technosols constructed in mining areas can become excellent carbon sinks if properly designed for this purpose.

Keywords: technosols, greenhouse gases reduction, recovery of degraded areas, coal mining, polynomial regression

1. Introduction

In Brazil, coal reserves are concentrated in the State of Rio Grande do Sul (RS), which holds approximately 80% of the country's coal reserves. In the municipality of Candiota, in the Campanha region, there is the largest surface coal mine, operated by Companhia Riograndense de Mineração (CRM) since 1961, with around one billion tons, at depths of up to 50 m. Although coal mining for energy production can be considered a strategic resource for national development [1], it is also one of the most

harmful anthropogenic activities, causing large-scale impacts on ecosystems, such as the degradation of soil, pollution of water resources and loss of biodiversity. The magnitude of the environmental impact of these activities depends on the mining technologies used, the extent of the disturbance, chemical, physical and biological factors, mineralogical composition of the soil, vegetation cover, topography, hydrogeological features, and the recovery method used after mining closure. The surface mining causes the following impacts in the areas [2]: it eliminates vegetation; significantly changes the topography; modifies the structure of the soil, subsoil and the geological column drastically and permanently, and disturbs surface and underground hydrological regimes.

In general, the recovery of mined areas consists of relocating the surface layer of soil after removing the coal cover layer and relocating the geological materials to the previous open pit completing the topographic reconstruction stage of the landscape. However, the removal and deposition of the topsoil layer results in degradation of soil quality. Actually, the soils in these areas should be constructed in order to recover the quality of degraded areas after mining activities. Soil types that use mining residues and other types of anthropogenic residues or artifacts are classified as Technosols [3]. The most extensive technosols related to mined areas are mainly associated with modern landscapes created by surface coal mining and are classified as Spolic Technosols, based on the fact that they contain technogenic artifacts in the form of residues from mining activity [4]. In general, constructed technosols could recover most of the basic soil functions and ecosystem services expected for healthy soils [5].

The construction methods for technosols at the Candiota mine, RS, adopted by CRM (**Figure 1**), sometimes use thin topsoil thickness and, therefore, create technosols with a large amount of overburden materials just below these thin topsoil layers, which promotes greater soil density, lower macro-porosity, and high mechanical resistance to penetration, in addition to a low pH value (around 2.4). These soils are constructed with a profile basically composed of two layers: a surface one of topsoil consisting of the A horizon, often mixed with parts of the B and C horizons, and a subsurface composed of a mixture of overburden materials (saprolites and rocks, including a non-mined coal layer from the cover layer above the explored coal seams) [4]. The main steps involved in the construction of technosols at the Candiota mine are the following: (a) removal of the A, B and/or C horizons of the original soil, which are transported by trucks for final coverage of a topographically leveled area; (b) removal of cover rocks using a high-capacity excavator (dragline); (c) extraction of coal banks; (d) in the pit opened by coal extraction, overburden (a mixture of rocks and unused coal) is deposited, which is leveled by bulldozers during the topographic recomposition of the area; (e) completing the topographic reconstruction of the area, a layer of soil (horizon A and/or B) is deposited (topsoil), removed prior to coal mining [7].

Soil compaction is considered the main physical impact on the construction of these technosols. The high compaction is caused by the intense traffic of heavy machinery during the topographic recomposition of the degraded area and has consequences, above all, on the revegetation of these areas [8–10]. The impact of machine traffic at the time of soil reconstruction cause a 23.53% increase in Bd, by immediately after the first pass of the tractor, causing a 20% decrease in total porosity. As a result of the soil compression process, after 12 tractor passes, the percentage of macroaggregates increased from 22.56 to 36.58% [11]. The transit of large machines promotes densification of the layers, reducing the volume of pores and the moisture content of the soil, favoring the connections between mineral particles [12], restricting soil

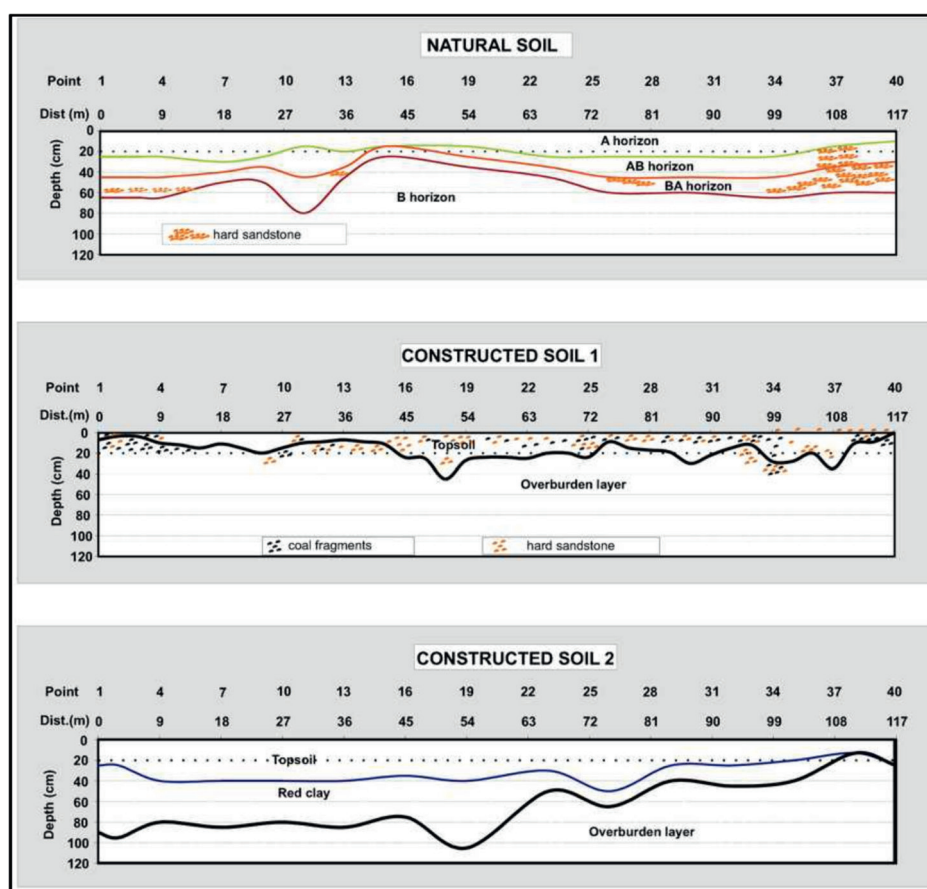


Figure 1.
 General sketch of the morphological variation of a natural soil (SN), constructed soil 1 (SC1) and constructed soil 2 (SC2), along profiles and transects, in CRM recovery areas, in Candiota, RS, prior to 1999. Source: [6].

aeration, compromising the root respiration and the development of microorganism populations, due to the significant reduction in soil macro and microporosity. The topographic recomposition and spreading of topsoil with heavy equipment result in the loss of soil structure, determining, among other changes, an increase in soil bulk density ($Bd > 1.6 \text{ Mg m}^{-3}$) and low rates of infiltration of water into the soil ($VIB < 5 \text{ cm h}^{-1}$), conditions that favor surface runoff and water erosion [13]. This effect can be observed in **Table 1** where Bd , total porosity (TP) and macro-porosity (Ma) are related to the basic soil water infiltration rates (IR) in technosols (CT1 and CT2) and in natural soil (NS). In relation to natural soil, soils constructed with 1 and 5 years of age have higher density and lower total porosity. The lower IR value in natural soil compared to the technosols is probably due to the Ma index of natural soil, which is relatively lower along practically the entire transect; as its soil density values are lower and its TP values are higher [14]. The very low Ma of the natural soil indicates that this soil must have been degraded by previous use, with excessive cultivation, prolonged periods without vegetation cover and/or trampling by live-stock. Furthermore, as it is in a mining front area, this soil may have suffered heavy equipment traffic [6].

Soil	Bd (Mg m ⁻³)	PT (m ⁻³ m ⁻³)	Ma (m ⁻³ m ⁻³)	IR (mm h ⁻¹)		
				Mean	Minimum	Maximum
NS	1.42 b	0.4042 a	0.0120 c	0.59 b	0.23	1.10
CT1	1.61 a	0.3510 b	0.0438 b	8.69 a	0.78	35.98
CT2	1.59 a	0.3495 b	0.0577 a	7.33 a	1.20	27.34

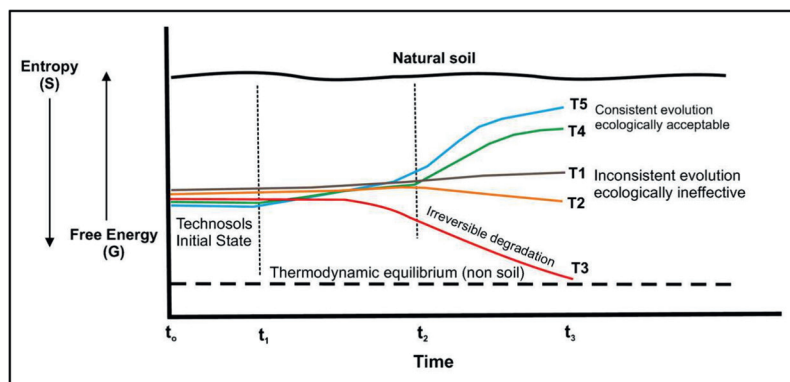
Values followed by the same letter in the column do not differ significantly at the $\alpha = 0.05$ level, using the Tukey test.
Source: Authors, adapted from [6, 14].

Table 1.

Mean of soil bulk density (Bd), total porosity (TP), macro-porosity (Ma), basic infiltration rate (IR) of natural (NS), constructed technosol 1 (CT1) and constructed technosol 2 (CT2) soils.

Over the last 20 years, several physical, chemical and biological variables have been monitored in an experiment with perennial grasses, installed in an area under recovery at the Candiota mine, RS. During this period, great difficulty was encountered in revegetating technosols and, consequently, in the natural incorporation of organic residues, directly and negatively influencing the recovery of these areas [15]. However, during this period, the species *Hemarthria altissima* and *U. brizantha* have demonstrated their great capacity to promote soil decompression [9, 16] and contribute large amounts of organic residues [10, 17–19], proving to be highly effective in reducing Bd and increasing TOC in these technosols.

Despite the enormous effort in monitoring and analyzing the various variables studied, no mathematical model was adjusted to the observed data to describe the behavior and development of the constructed technosols. In this regard, a thermodynamic approach to the evolution of technosols conceptually describes the evolution of these soils [4]. Considering them as open systems far from equilibrium, the flows of matter and energy that enter the system would develop over three phases, as illustrated in **Figure 2**. In the first phase (between t_0 and t_1), they will be at an initial stage (first years) in which the sources of matter and energy (organic matter and microbiota) are in a latent state. Between t_1 and t_2 , the flows of matter and energy will be active, in different ways, depending on the type of treatment (T1 – T5), but in a statistically indistinguishable way. From t_2 and t_3 , significant statistical differences will be easily evident

**Figure 2.**

Hypothetical evolution of technosols constructed in mining areas, under different treatments (T1 to T5), related to different levels of thermodynamic organization. Source: [4].

and technosol will be able to evolve into different future scenarios: (a) irreversible soil degradation (T3); (b) very slow and insufficient evolution to reactivate the local ecosystem (recovery over “time”); (c) the reactivation of flows of matter and energy capable of bringing “life” back to the location (ecosystem recomposed at an acceptable level).

In general, the studies carried out to date in the experimental area of the Candiota mine start from the perspective of a future agro silvopastoral use of the recovered areas. Moreover, technosols constructed in mined areas have a great potential to accumulate significant amounts of carbon, although their ability to function as large-scale carbon sinks and their implications for the global greenhouse gases (GHGs) reduction effort have not yet been assessed. Currently, the enormous losses of carbon stocks, due to changes in land use and management, induced by human activities [20], where mining activities stand out, have led governments to develop sustainable management policies in order to face potential threats of soil degradation, so that their ability to provide essential services is protected or improved [21]. On the other hand, the increase in the concentration of GHG in the atmosphere, especially in recent decades [22], has stimulated the development and consolidation of technologies that allow soils to act as drains for atmospheric C [23].

From this perspective, the recovery of areas degraded by mining activities has received, in recent decades, great attention due to its possible role in combating global warming. Several studies emphasize the interrelationship between the environmental recovery of these areas, C sequestration and nutrient reservoirs [2, 5, 24–28]. Technosols revegetated after mineral exploration can be a significant sink of atmospheric CO₂ through the formation of soil organic matter (SOM) and accumulation of aboveground biomass. In their initial stage of development, technosols offer excellent opportunities for recycling organic waste and maximizing their potential as a carbon sink in relation to agricultural soils, through the adoption of construction and management techniques that enable high rates of carbon sequestration. Proper revegetation of mined areas is an important process to sequester large amounts of atmospheric C and return the land to a stable state [29]. The vegetation of these areas is one of the factors that most contributes to increasing the speed of soil formation in the initial stages of pedogenesis in technosols [30]. Increasing organic matter is an essential factor when seeking to recover soils from areas degraded by mining. The SOM has long been recognized as a universal indicator of soil quality, since it interacts with several soil constituents, influencing water retention, aggregate formation, soil density, pH, cation exchange, nutrient mineralization, sorption of pesticides and other agrochemicals, infiltration, aeration and biological activity of the soil [31].

This study aimed to evaluate the evolution of organic matter indices incorporated by perennial grasses, over 15 years, in a technosol constructed in 2003, as well as its dynamics and interaction with other soil recovery factors and obtain an estimate of carbon stocks incorporated by *H. altissima* and *U. brizantha*.

2. Material and methods

The experiment was installed in a technosol constructed by Companhia Riograndense de Mineração (CRM), in an area under recovery, located in the municipality of Candiota, RS, at geographic coordinates 31° 33' 55.5"S, 53° 43' 30, 6"W and altitude of 230 m. The region has a humid subtropical climate, type Cfa [32], with an average annual temperature of 17.2°C, with the highest average temperatures in February (24.2°C) and the lowest in July (12.2°C). The absolute maximum

temperature recorded was 45°C and the minimum −2.0°C. The Candiota region has an average annual rainfall of 1599.9 mm, well distributed throughout the year, with a monthly average of 133.3 mm. The highest average precipitation values were observed in the months of April (173.2 mm) and October (176.0 mm). The months of January, February, March, November and December present greater evapotranspiration than precipitation, as the average temperature of these months is higher due to the summer season (**Figure 3**).

The results of the climatological water balance [34] highlighted the months of January, February, March, November and December as having a water deficit while the remaining months had a water surplus (**Figure 4**). The water deficit value in the period was 167.0 mm for the period of a climatological normal (1991–2020), verified between the months of November to March, with values in the following order of magnitude: November (69.7 mm); December (38.6 mm); January (24.4 mm); February (19.4 mm) and March (14.9 mm). The month of December stands out as having the lowest monthly rainfall (114 mm), while the highest average rainfall rates recorded in the period 1991–2020 occurred in the months of April and October, and the excess water calculated in the present study it was 324.3 mm.

The surface mining developed by CRM, in Candiota, RS, impacts an area of 750 ha, of which approximately 610 ha has been topographically recomposed with topsoil (mixture of horizons A, B and C) and 690 ha are under vegetation recovery [35]. The mineral exploration area is divided into 15 grids where, in grid VII, the studied experimental area was installed.

The technosol in the experimental area is characterized by a under layer formed by overburden materials (fragmented mudstones, shales, carbonaceous shales and sandstones removed by detonation of the coal seam cover). The top layer comes from a natural soil from a pre-mined area, classified as Rhodic Lixisol, clayey textural class, dark red color (2.5 YR 3.5/6) and low organic matter content (1.15%) [6]. This top layer (approximately 15–20 cm) is predominantly formed by B horizon mixed with A horizon, removed prior to coal extraction and relocated again as topsoil in areas undergoing recovery [36, 37].

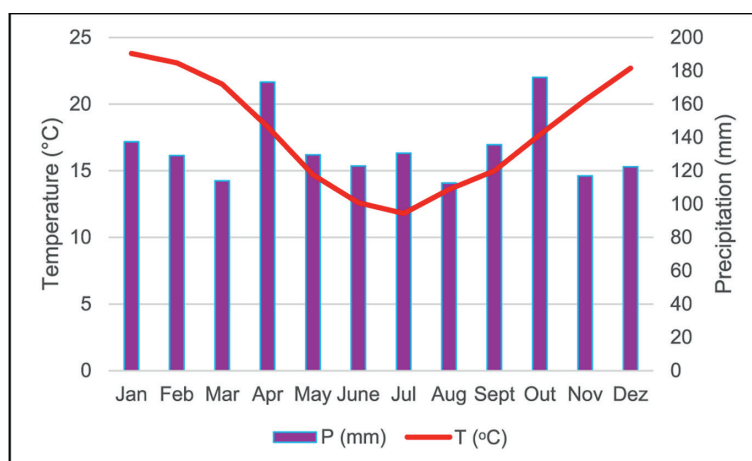


Figure 3. Annual thermopluviometric variation for the municipality of Bagé, RS, from 1991 to 2020. Source: Authors. Data: [33].

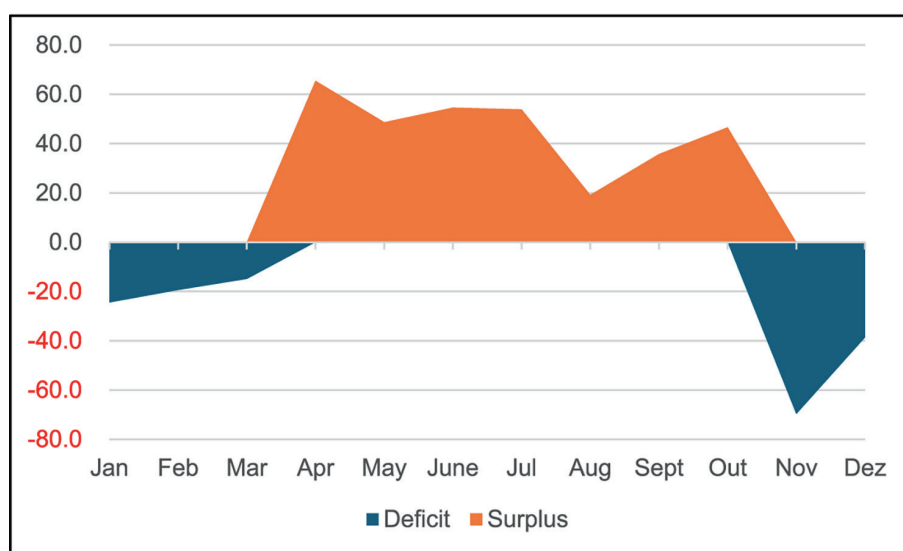


Figure 4.
Water surpluses and deficits (mm) in the municipality of Bagé, from 1991 to 2020. Source: Authors. Data: [33].

Before the experiment was set up, in September 2003, the soil in the area was scarified to a depth of 0.10 to 0.15 m. Next, 10.4 t ha⁻¹ of limestone was applied and incorporated, and 900 kg of mineral fertilizer in the 5-20-20 formula, according to the results of the soil analysis. Nitrogen fertilization with ammonium sulfate at a dose of 40 kg ha⁻¹ and manual weeding with a hoe were also carried out whenever invasives appeared in the area. Annual fertilizations were carried out on all plots, applying 350 kg ha⁻¹, with formulation 5-30-15 and 250 kg ha⁻¹ of ammonium sulfate [37].

Between November and December 2003 different species of cover plants (annual and perennial) were sown. The experiment was installed in plots of 20 m² (5 m × 4 m), in a randomized block design, with divided plots, with four replications. Summer crops were arranged in the plots and winter crops in subplots [38]. Perennial summer grasses were used in the plots, with a summer period in winter, single or intercropped with Pinto Peanut (*Arachis pintoi*), composing the following treatments (**Figure 5**).

- T1 – *Hemarthria altissima* (Poiz.) Staff & C. E. Huhh,
- T2 – *Cynodon dactylum* (L.) Pers. cv. Tifton 85 + *Arachis pintoi*,
- T3 – *Hemarthria altissima* (Poiz.) Staff & C. E. Huhh + *Arachis pintoi*,
- T4 – *Paspalum notatum* Flüggé Var. *sausae* Pacodi cv. Pensacola,
- T5 – *Cynodon dactylum* (L.) Pers. cv Tifton 85,
- T6 – *Paspalum notatum* Flüggé Var. *sausae* Pacodi cv. Pensacola+ *Arachis pintoi*,
- T7 – *Urochloa brizantha*
- T8 – Natural soil.

The *A. pintoii*, despite initial development, had its growth reduced over time and practically disappeared in the third year (2006). The same happened with the *Festuca arundinacea* and *Lotus pedunculatus* [38]. With this, the experiment was reduced to only single poaceas: *H. altissima* (T1), *Cynodon dactylum* (T4), *Paspalum notatum* (T5), *U. brizantha* (T7) and the control treatments [37]. The treatments were named as follows: *H. altissima* (T1), *Paspalum notatum* (T2), *Cynodon dactylum* (T3) and *U. brizantha* (T4). For comparative purposes, in areas adjacent to the experiment, the same soil constructed without vegetation cover and samples of natural soil, from the mining front, occupied by native vegetation (shrub and herbaceous) were used.

In the following years (2004, 2005 and 2006), the area was cultivated with black oat (*Avena strigosa*) in the winter and, every summer, treatments were again attempted to be implemented with different species of single and/or intercropped cover crops. In May 2007, when oats were planted, the area was fertilized again with a dose equivalent to 750 kg ha^{-1} (formula 5-20-20). During the entire period, nitrogen was occasionally applied with ammonium sulfate [36].

For 15 years, from May 2004 to April 2018, several works carried out in the experimental area monitored and evaluated the recovery of soils degraded by coal mining in Candiota [7, 37–41]. During this period, several variables were evaluated that describe physical, chemical and biological characteristics of the soil, two of which were considered in this study: soil density (Bd) and total organic carbon content (TOC), both measured in the 0.00–0.10 m layer. Of the species implemented and monitored since 2003, the Poaceae *H. altissima* and *U. brizantha* were selected for this study. The selection of these species prioritized the amount of biomass produced and their adaptation to local soil and climate conditions. This is because the region of Candiota, RS, experiences periods of water deficit in the

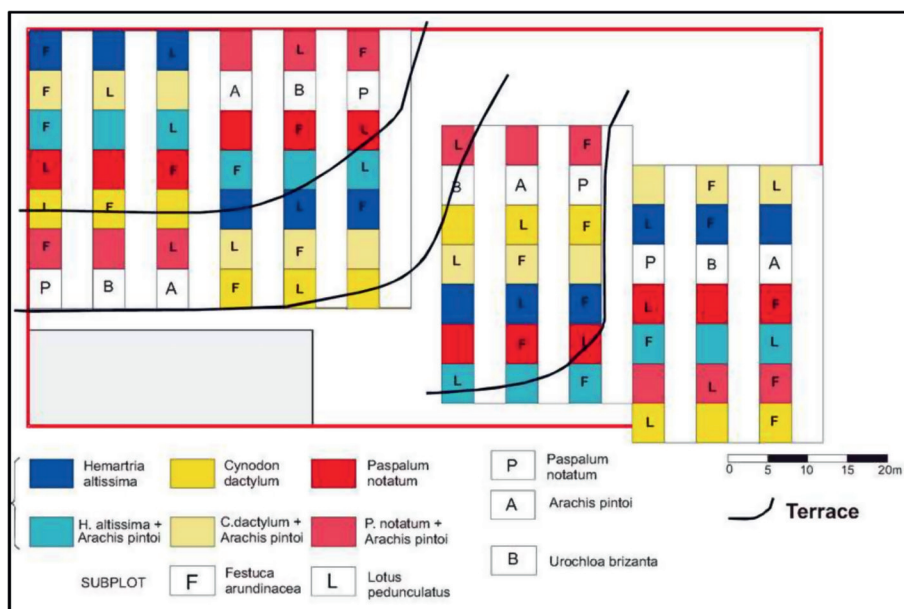


Figure 5. Sketch of the experimental area, implemented between November and December 2003, in the CRM mining area, in Candiota, RS. Source: Authors.

summer and low temperatures in the winter. Furthermore, they must withstand sites of varying alkalinity and acidity due to the use of limestone and the pyrite oxidation process, which may be mixed with the source material that serves as topsoil.

Fast-growing grasses such as *H. altissima* and *U. brizantha* have a root system that provides better soil coverage rates and can favor the recovery process of areas degraded, preventing soil disintegration [12]. *U. brizantha* is a tropical perennial grass, with loose tufts with short rhizomes and erect or slightly decumbent stems 60–150 (<200) cm high, used as a soil cover to control erosion. Widely distributed, it is best adapted to the humid and sub-humid tropics with average annual precipitation of 1500–3500 mm, but it also grows in more arid tropical regions, with precipitation just below 1000 mm, and can withstand dry seasons of 3 to 6 months. The *U. brizantha* grows in a wide range of well-drained, medium to clayey soils with pH 4–8. It is tolerant to high concentrations of Al^{+3} and is often found in soils with pH < 5.5. Mn tolerance varies between ecotypes, although it can survive in low fertility soils, it requires medium to high soil fertility to be productive. The *H. altissima* is a perennial grass with short rhizomes; culms loosely tufted or prostrate to decumbent, 100–250 cm long, 2–4 mm in diameter, rooting at lower nodes, rising to 30–80 (<160) cm tall. The *H. altissima* grows in soils of any texture, if the humidity is adequate. It produces few seeds, so it is propagated through seedlings (stolon cuttings) planted in moist soil. It tolerates acidic soils up to pH 4.5, but performs best between 5.5 and 6.5 and has a high level of tolerance to excess Al and Mg. It is found in flooded areas, swamps, lakes, however, it can withstand short periods of seasonal drought. It has high growth speed and high biomass addition potential for longer periods than other tropical grasses. As it is found naturally between latitudes of 40°N and 34°S, it tolerates heat (optimal development between 31 and 35°C), frost and cold temperatures of up to –10°C. Its tolerance to low pH and high Al and Mn could be usefully applied to the revegetation of acid mine waste where moisture conditions are suitable [42].

2.1 Statistical analysis

The data considered in this study refer to the Bd and TOC variables, evaluated in plots covered with the grasses *H. altissima* and *U. brizantha*, over a period of 15 years (2003 to 2018). As variable assessments were repeated over time at intervals of varying amplitude, time was measured in months. Thus, six levels were considered for the Time factor: 5, 41, 78, 103, 132 and 175 months after the installation of the experiment.

The statistical analysis of the data comprised the techniques of analysis of variance, to test the significance of the main effects and the interaction of the factors Grass and Time, and polynomial regression analysis to discriminate the variation of the Time factor. For all tests, the significance level $\alpha = 0.05$ was adopted.

Polynomial regression models (Eq. 1) were adjusted for TOC and Bd data in order to identify those that best describe the behavior of these variables over time. The analyses were processed using the statistical analysis system for Windows – Winstat [43].

Polynomial regression is used to describe the relationship between the predictor variable x (Time) and the response variable y (TOC or Bd) as a polynomial of the n th degree in x [44, 45]. The generic form of the n th order polynomial regression equation with a single predictor variable can be represented in the following form:

$$y = \beta_0 + \beta_1 \cdot x + \beta_2 \cdot x^2 + \dots + \beta_n \cdot x^n + \varepsilon \quad (1)$$

Where: y is the response variable; x is the predictor variable, β_i are model parameters and ε is the random error.

Estimates of total organic carbon stocks (SCS), stored in soils under *H. altissima* and *U. brizantha* treatments, were calculated [46] using the native soil density of the mining front area as a correction factor.

3. Results and discussion

The results of the analysis of variance, for the TOC and Bd variables, indicate that the main effect of the Time factor was highly significant ($p < 0.0001$), while the main effect of the Grass factor and the interaction between the Grass and Time factors were not significant (**Table 2**). The absence of interaction indicates that the behavior of the response variable over time is the same for both grass species and that the effect of the Grass factor is the same at all levels of the Time factor. The significance of the main effect of the Time factor indicates that the polynomial regression adjustment must be carried out for the marginal means of the Time factor levels.

3.1 The evolution of the technosol over 15 years of monitoring

The polynomial regression adjusted to the observed data is presented in **Figure 6**. Two criteria are used to choose the polynomial regression model: the significance of the model and the magnitude of the value of the coefficient of determination (R^2). For the TOC variable, the linear ($p < 0.0001$) and cubic ($p = 0.0099$) models were highly significant. The adjustment of these models to the observed data obtained indices of $R^2 = 75.24$ (Eq. 2) and $R^2 = 98.89$ (Eq. 3), respectively. The high value of R^2 verified for the cubic model indicates this model as an excellent descriptor of the behavior of TOC data throughout the evolution of the technosol.

$$\hat{\mu} = 2.8461 + 0.09487x \quad (2)$$

$$\hat{\mu} = 4.5866 + 0.1670x - 0.0024x^2 + 1.2059 \cdot 10^{-5}x^3 \quad (3)$$

The **Figure 6** shows the linear and cubic models, adjusted to data observed between 2004 (5 months) and 2018 (175 months). In 15 years of recovery, the accumulation of organic matter (TOC) in treatments cultivated with *H. altissima* and *U. brizantha* increased by 465%. The initial TOC values after 5 months of implementation of the experiment were 5.36 g kg^{-1} and after 175 months they reached an index of 24.94 g kg^{-1} , higher than that found for natural soil (22.72 g kg^{-1}). It can also be seen, in **Figure 7**, that at 175 months some of the TOC observations exceeded the value of 30 g kg^{-1} .

The development of the polynomial model comprises two subsequent waves, each consisting of three sampling campaigns: the first wave is described by data collected at 5, 41 and 78 months and the second wave corresponds to data collected at 103, 132 and 175 months, after the implementation of the experimental area.

Grass	TOC							Bd						
	Time (months)							Time (months)						
	5	41	78	103	132	175	Mean	5	41	78	103	132	175	Mean
<i>U. brizantha</i>	5.48	7.98	10.20	8.40	12.60	24.04	11.45 a	1.40	1.57	1.37	1.23	1.27	1.33	1.36 a
<i>H. altissima</i>	5.22	8.24	8.48	7.67	13.02	24.17	11.13 a	1.47	1.57	1.45	1.40	1.36	1.37	1.44 a
Mean	5.35	8.11	9.34	8.03	12.81	24.10	11.29	1.44	1.57	1.41	1.31	1.31	1.35	1.40

Note: Means followed by the same letter in the column do not differ from each other, using the F test, at the level $\alpha = 0.05$.

Table 2.
 Means of the variables total organic carbon (TOC) and soil bulk density (Bd), according to the factors Grass and Time.

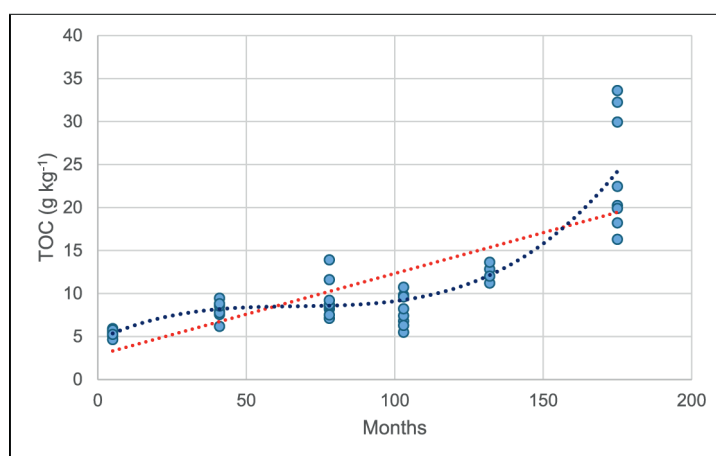


Figure 6.

Linear and cubic models adjusted to TOC data from *H. altissima* and *U. brizantha*, over 15 years of observations (175 months), between 2003 and 2018. Source: Authors.

3.2 The first wave of TOC growth: from implementation to 78 months of the experiment

The first wave of TOC growth is comprehended by observations carried out in the first 7 years after the installation of the experiment [38–40]. Considering the thermodynamic model of technosol evolution, this wave would correspond to the first and second phases described [4], where the development of the product takes place from a latent state (1st phase) to a state where statistical differences will be evident (2nd phase). The 1st phase corresponds to the data observed in 2004 [40] and 2006 [38], in the first 48 months of the experiment, when no statistical difference, between the different variables analyzed, was significant. The 2nd phase begins with observations made in 2010 [38], at 78 months and ends at the beginning of the second wave of the model, at 103 months [7]. The estimated TOC values, observed at 5, 41 and 78 months, were 5.22, 8.23 and 8.73 g kg⁻¹ respectively. This range of values is considered “low” [47] and is far from the carbon content observed in natural soil taken as a reference (22.72 g kg⁻¹) [6]. However, during this observation period (73 months) there was an increase of 62.8% in the TOC index. However, during this observation period there was an increase of 62.8% in the TOC index. These results correspond to an annual growth rate in the TOC index of 55.4%, in the 1st phase of technosol evolution. This initial effect of the experiment may reflect, in addition to the incorporation of dry matter by cultivated grasses, the numerous attempts to implement the legumes *A. pinto* and *L. pedunculatus*, as well as other grasses such as *A. strigosa* and *Festuca arundinacea*. It is considered that the various attempts to implement these crops contributed important contributions of dry matter between 2003 and 2006, when attempts to implement legumes as a source of N to the soil were abandoned.

In the 1st and 2nd phases of technosols development, carbon mineralization tends to be very intense right after the incorporation of organic matter into the soil, then progressively slows down until reaching a stage in which little mineralization occurs, and the organic matter that remains is, if not “sequestered”, at least stabilized and no longer accessible to microorganisms or their exoenzymes. The kinetics of organic matter in the soil is described by a logarithmic equation where half of the organic

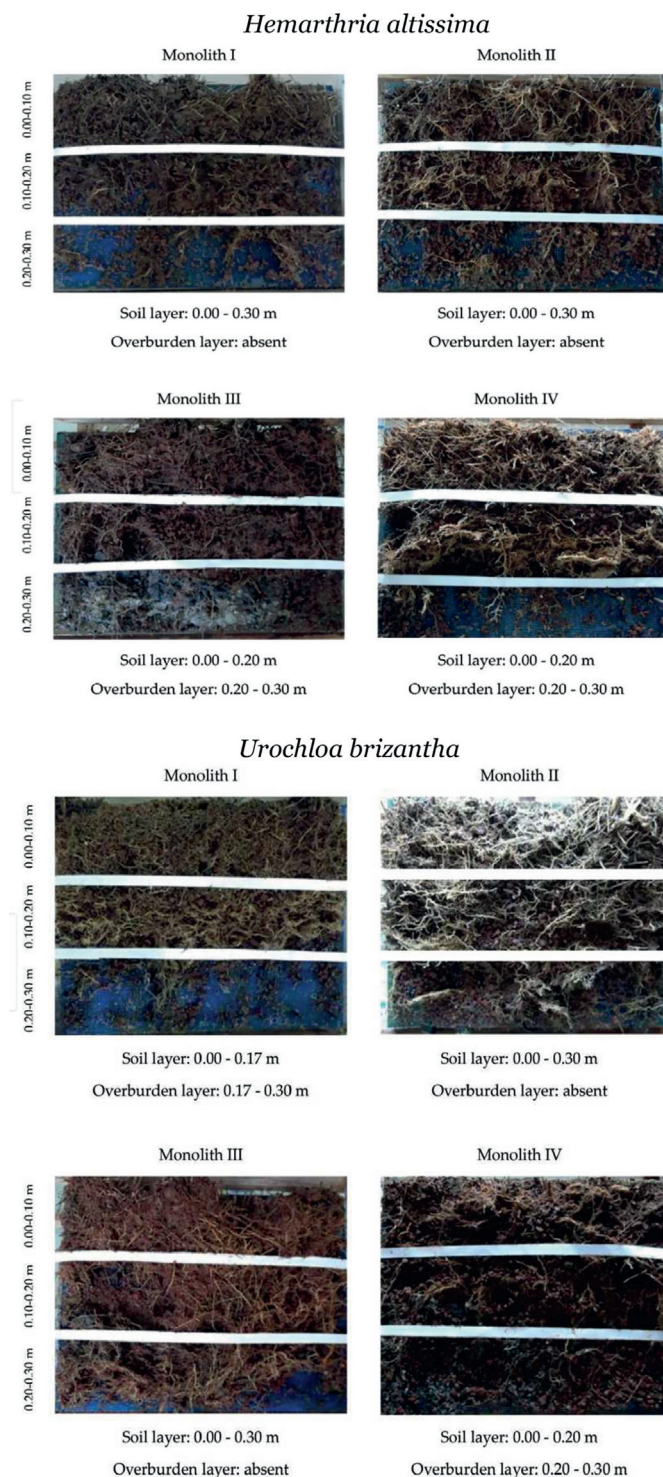


Figure 7.
Qualitative evaluation of the roots at 103 months of revegetation, after washing the soil monoliths removed to a depth of 0.30 m and the thickness of the soil and overburden layer in treatments with *H. altissima* and *U. brizantha*. Source: [7].

matter added to the soil is mineralized after just over a year, 80% disappears after 7 years and the amount of organic matter remaining after 30 years it is only a tenth of that initially applied [48]. In the case of the incorporation of organic matter into the soil, this behavior can be described by a succession of exponential equations, which can be described by polynomial models such as those shown in the **Figure 6**.

Another important aspect to highlight is the enormous variations observed in several monitored variables, observed in the collections carried out in the months of May 2004, November 2004 and May 2005 [19]. It is believed that such differences are due to climate variations between these months. As can be seen in **Figures 2 and 3**, where regional thermopluviometric variations and climatological water balance are presented, respectively, the temperature variation between May (14.7°C) and November (20.3°C) is, in average, around 5.6°C. Another important climatic aspect associated with the collection periods is that in the month of May there is a surplus of rainfall, while in November the period of water deficit begins in the Candiota region. Thus, under high rates of chemical weathering, such as those found in tropical or subtropical climates, technosols constructed with significant amounts of easily weatherable minerals have the potential to function as efficient carbon sinks [24]. The high potential for soil carbon stocks (SCS) recovery with technosols, particularly in tropical regions, can be attributed to the high input of plant-derived carbon and the strong potential for carbon stabilization through mineral-organic interactions.

3.3 The second wave of TOC growth: from 103 to 175 months

The second wave described by the cubic model, for the increase in TOC, is between 103 and 175 months after the implementation of the experimental area [7, 37, 49]. The average TOC values observed in this period were respectively 9,50, 12,54 e 24,94 g kg⁻¹. During this period, a much more pronounced growth in TOC rates can be seen. The TOC growth rate in this period was 262,4%. This result corresponds to a growth rate of 43,7% year⁻¹. This result shows that the deposition of plant residues, added to the greater root development of grasses in the 0.00–0.10 m layer, contributed to the greater increase in TOC on the surface of the technosol. When evaluating the root system of the grasses established in the experiment, it was found that *U. brizantha* presented the highest root density, in the layer of 0.00–0.10 m (13.29 kg m⁻³) in relation to the other species. In the 0.00–0.10 m layer, the root volume of *U. brizantha* (0.032 m³ m⁻³) and *H. altissima* (0.023 m³ m⁻³) did not show significant differences between them (Tukey test, $\alpha = 0.05$), but they were significantly superior to the other grasses evaluated. It is considered that the greater concentration of roots on the surface of the constructed soil may be due to physical or chemical limitations of the underlying layers at 0.10 m, which did not allow for a more uniform development of roots in depth, as can be seen in **Figure 7** [7].

After 132 months of revegetation with grasses, the density of mites and springtails was significantly higher in the treatment with *H. altissima* [37]. It was observed that lower organic carbon values directly affect the permanence of soil mesofauna organisms in the different treatments in the area under study.

3.4 Effects of increasing TOC on soil bulk density (Bd)

The evolution over the 15 years of monitoring Bd in relation to TOC can be seen in **Figure 8**. The grasses did not show significant differences between them in reducing Bd over this period. The linear regression adjusted to the observed Bd data

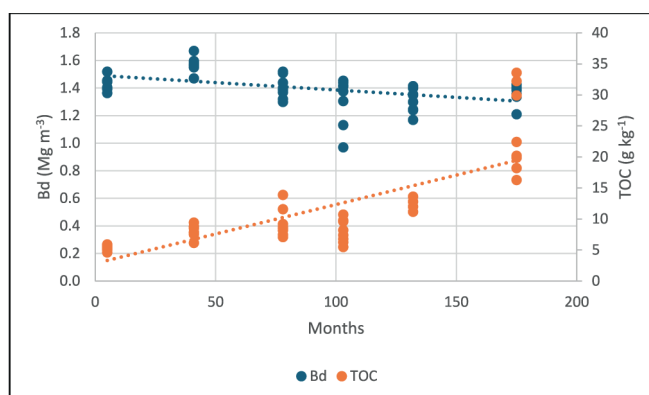


Figure 8.
Variation over 15 years of observation in soil bulk density (Bd) and total organic carbon (TOC) in treatments under cultivation of *H. altissima* and *U. brizantha*, in the experimental area of Candiota, RS. Source: authors.

resulted highly significant over time ($p < 0,0001$), with a coefficient of determination $R^2 = 47.57$ (Eq. 4). The Bd estimated by this model reduced from 1.49 g kg^{-1} at 5 months (2004) to 1.30 g kg^{-1} at 175 months (2018), representing an 83% reduction in relation to the initial values observed.

$$\hat{\mu} = 1.4945 - 0.0011x \quad (4)$$

The linear models show that, as the technosol evolves over time, TOC rates increase and Bd decreases. These results agree with other studies [49, 50] that found increases in TOC levels and reductions in Bd as recovery years progressed in different soils, regardless of the type of vegetation. Contrary to some observations [51], the overall relationship between compaction-induced changes in C mineralization and Bd resulted in linear regressions with opposite directions. This means that as the amount of carbon incorporated into the soil increases, the soil density reduces. This is mainly due to the root growth of the grasses under study which, as they increase their density, simultaneously promote the breakdown of aggregates formed by intense soil compaction and increase organic carbon levels through root decomposition. It is noted that, as TOC stocks increase, Bd reduces its intensity. These results converge with other studies that found that vegetation development is strongly correlated with improvements in organic matter and soil bulk density [52, 53].

Although the differences were not significant over the monitoring period, *H. altissima* presented the highest TOC contributions, while its ability to reduce Bd was relatively lower when compared to the reduction promoted by *U. brizantha*. In 2004, the average soil Bd under *H. altissima* was 1.47 Mg m^{-3} and, in 2018, it resulted in 1.45 Mg m^{-3} , while *U. brizantha* presented an average Bd of 1.40 Mg m^{-3} in 2004 and, in 2018, resulted in 1.19 Mg m^{-3} . In 2004, *U. brizantha* showed significant differences in Bd, in the 0.00–0.10 m layer, in relation to other cultivated grasses [39], highlighting the capacity of its root system to occupy the pore spaces of highly compacted soils.

3.5 Technosols in coal mining areas as carbon sinks

After 15 years of recovery with perennial grasses, it was observed that soil carbon stocks (SCS) varied from 5.42 Mg ha^{-1} (5 months) to 22.39 Mg ha^{-1} (175 months)

in treatment under *U. brizantha* and from 5.16 Mg ha⁻¹ to 22.51 Mg ha⁻¹ under *H. altissima*, with no statistical difference between treatments (**Figure 9**). After 175 months of implementation of the experiment, *H. altissima* and *U. brizantha* increased the SCS, on average, by 17.60 Mg ha⁻¹ (425%), in relation to 2004. It is noteworthy that throughout the first wave of technosol development (5 to 103 months), the average SCS growth was 0.20 Mg ha⁻¹ year⁻¹ (16% year⁻¹), a period that corresponds to the 1st and 2nd phases of technosol evolution [4]. Between 103 and 132 months, the SCS increased at a rate of 2.34 Mg ha⁻¹ year⁻¹ (68% year⁻¹) when, there is a new increase in the growth rate, which reaches 3.08 Mg ha⁻¹ year⁻¹ at 175 months (55% year⁻¹). These results highlight the great capacity that these grass species have to improve organic matter levels in the soil, both due to their large production of dry matter and their root system.

In Europe and the United States, rates between 0.2 and 2.0 Mg C ha⁻¹ year⁻¹ were used to predict the effects of reclamation of mined land. Accumulation rates in permanent pastures were relatively higher than other crops, ranging from 0.48 to 1.1 Mg ha⁻¹ year⁻¹, in dry tropical lands to cold temperate steppes. Technosols have the potential to sequester carbon and incorporate it in the form of organic matter into the soil, especially in the first years after the start of recovery of the degraded area and may exceed the organic carbon stocks of the original soil [28].

In India, revegetated mined areas compensate 1.20 Mg C ha⁻¹ year⁻¹ by CO₂ sequestration in the soil, while the total compensation potential through soil, biomass and litter mass is 9.36 Mg ha⁻¹ year⁻¹. Therefore, technosols can be considered significant sinks of atmospheric CO₂ through vegetation development, together with ecosystem redevelopment and soil formation. Revegetation of mining areas deserves serious consideration due to its potential to sequester SCS long enough to offset C emissions. Successful revegetation can also serve as a cost-effective way to mitigate the growing problem of CO₂ accumulation in the atmosphere. However, a long-term study on the productivity of these soils is necessary to identify sustainable management options and evaluate C sequestration over a long period of time [27].

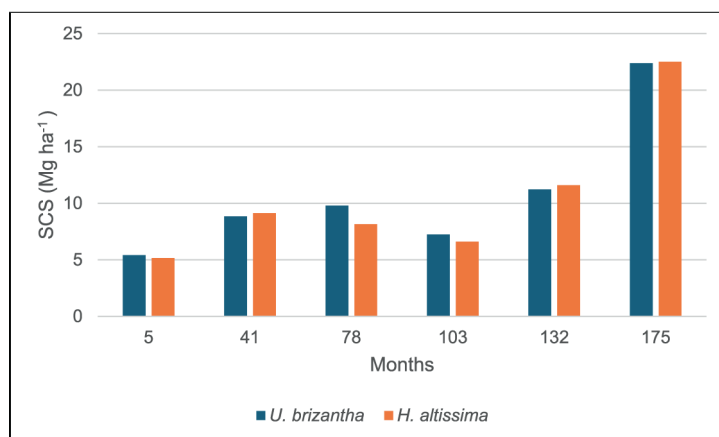


Figure 9.

Evolution of organic carbon stocks (Mg ha⁻¹), in the 0.00–0.10 m layer, produced by *H. altissima* and *U. brizantha*, over 15 years (175 months) of recovery of a constructed technosol in surface mining coal area, in Candiota, RS. Source: authors.

4. Final considerations

Several studies have sought to develop quality indices for technosols constructed in mined areas with the aim of investigating the influence of the time factor on the recovery of these areas [54, 55]. In general, these indices are made from chronosequences with different technosols constructed at different times and different source materials and types of waste. In this way, quality indices linked to different variables can be evaluated using different regressive mathematical models. Our study, differing from these, does not require such an approach, as it was implemented in an area intended for research, with experimental control in a randomized block design [16]. The same technosol has been monitored over time and its properties compared to a “natural soil”, which makes the data obtained more reliable and the conclusions more robust and scientifically significant. In this study, in addition to generating a model, with high statistical significance and excellent adjustment to observed data, capable of describing the evolution of a technosol, over 15 years of observations, the potential of these technosols to contribute to the global effort to reduce of GHG.

The large impacts generated by coal mining for thermal power generation in terms of GHG emissions can be partially mitigated with technosols properly designed for this purpose and with vegetation management techniques that promote the rapid incorporation of waste into the soil [55]. In addition to topographic recomposition and revegetation of the degraded landscape, with a view to reducing damage caused by erosion processes to the new environments generated, technosols have great potential for use as carbon sinks.

Past precedence and research results show that the reclaimed soil properties in coal mining areas even after several years of reclamation are still evolving [16]. Hence, the most economical/cost effective and practical approach to bring the degraded soil to near natural soil is to ‘*leave the land as it is*’ (i.e., *in situ* and undisturbed). Slowly, over a period of time the cultivability of soil is restored automatically through many naturally active agents, carriers and natural unclaimed processes dominant in the mining areas. However, it is important to highlight that, in the beginning, correcting soil acidity and fertilization are essential for the implementation of crops to be used in the recovery of degraded areas.

Although the regression analysis pointed to the cubic model as an excellent descriptor of the evolution of the technosol in its first 15 years, other models will probably be developed as the years of monitoring progress. Considering the behavior presented by the set of observed data and the trend of accelerated growth in TOC indices, it is believed that the best descriptor of the long-term evolution behavior of technosols is best described by a succession of LRP-type regression models (linear response plateau). The LRP model is a type of regression segmented into two parts, where in the first part the response is described by a simple linear regression model and the other is described by one parallel to x (plateau), that is, where the response is constant [56]. In our chronosequence, this model would adapt to the set of data obtained in the first four evaluations [7, 38–40], of which the first two would correspond to simple linear regression and the remaining to Plateau.

5. Conclusions

The cubic model adjusted to data observed over 15 years of technosol monitoring, obtained high statistical significance and an excellent coefficient of determination, being able to robustly express the evolution of the technosol.

The grass species evaluated (*H. altissima* and *U. brizantha*) did not show significant differences between them, over 15 years of observations, in the incorporation of TOC, in soil carbon stocks and in the reduction of soil density.

Throughout this period, the TOC content in the surface layer of the soil exceeded the levels observed in the natural soil used as a comparison parameter.

The results presented in this study corroborate the importance of using perennial grasses as a technology capable of leading the evolution of technosols constructed in mining areas to the higher stages of the environmental recovery process.

Acknowledgements

The authors would like to acknowledge Companhia Riograndense de Mineração (CRM), Rede Carvão (Brazilian Coal Network), IBAMA (Brazilian Institute of the Environment and Renewable Natural Resources), CAPES and CNPq for logistical and financial support.

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

Luís Eduardo Torma Burgueño^{1*}, Luiz Fernando Spinelli Pinto², Lizete Stumpf²,
Clause Fátima de Brum Piana³, Maurício Silva de Oliveira¹, Maurizio Silveira Quadro⁴
and Pablo Miguel²

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

2 Agronomy Course, Soil Department, Federal University of Pelotas, Brazil

3 Technological Development Center, Federal University of Pelotas, Brazil

4 Engineering Center, Federal University of Pelotas, Brazil

*Address all correspondence to: eduardo.burgueno@gmail.com

IntechOpen

© 2024 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Brasil, 2023. Ministério de minas e energia. Empresa de Pesquisa Energética – EPE. Balanço Energético Nacional – BEN. Relatório Síntese 2023; Ano Base 2022. 65 p. Available from: <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-748/topico-687/BEN2023.pdf> [Accessed date: February 19, 2024]
- [2] Shrestha RK, Lal R. Ecosystem carbon budgeting and soil carbon sequestration in reclaimed mine soil. *Environment International*. 2006;**32**:781-796. DOI: 10.1016/j.envint.2006.05.001 [Accessed date: April 11, 2024]
- [3] WRB. Base de Referência Mundial para Recursos de Solo, 2014. Sistema Internacional de Classificação de Solos para Nomeação de Solos e Criação de Legendas para Mapas de Solos. Roma: FAO; 2014. 192 p. Relatórios Mundiais de Recursos do Solo. p. 106 [Accessed date: June 15, 2023]
- [4] Pinto LFS, Fernandes FF, Pauletto EA, Stumpf L. Recuperação de solos degradados pela mineração: da teoria termodinâmica à prática nas áreas regeneradas da mina de carvão de Candiota, RS. In: Alba JMF, editors. *Recuperação de áreas mineradas*. 3ª ed. Brasília, DF: Embrapa; 2018. 456 p. rev. e ampl
- [5] Ruiz F, Cherubin MR, Ferreira TO. Soil quality assessment of constructed Technosols: Towards the validation of a promising strategy for land reclamation, waste management and the recovery of soil functions. *Journal of Environmental Management*. 2020;**276**:111344. [Accessed date: October 12, 2023]
- [6] Nunes MCD. Condições físicas de solos construídos na área de mineração de carvão de Candiota-RS (Dissertação Mestrado em Ciências). Brazil: Programa de Pós-graduação em Agronomia, Universidade Federal de Pelotas, Faculdade de Agronomia Eliseu Maciel, Depto. de Solos; 2002, 131 p. Pelotas, RS, 2006, 120 p [Accessed date: June 14, 2023]
- [7] Stumpf L. Desenvolvimento radicular de gramíneas perenes e sua eficiência na recuperação de atributos físicos de um solo construído compactado em área de mineração de carvão Tese (Doutorado). Pelotas: Programa de Pós-Graduação em Agronomia, Faculdade de Agronomia Eliseu Maciel, Universidade Federal de Pelotas; 2015. 122 p [Accessed date: February 18, 2024]
- [8] Miguel P, Stumpf L, Pinto LFS, Pauletto EA, Rodrigues MF, Barboza LS, et al. Physical restoration of a minesoil after 10.6 years of revegetation. *Soil and Tillage Research*. 2023;**227**:105599. DOI: 10.1016/j.still.2022.105599 [Accessed date: September 13, 2023]
- [9] Pauletto EA, Stumpf L, Pinto LFS, Silva TS, Ambus JV, Garcia GF, et al. Reclamation of a degraded coal-mining area with perennial cover crops. *Revista Brasileira de Ciência do Solo*. 2016;**40**:e0150482. DOI: 10.1590/18069657rbcs20150482 [Accessed date: August 30, 2022]
- [10] Stumpf L, Pauletto EA, Fernandes FF, Suzuki LEAS, Silva TS, Pinto LFS, et al. Perennial grasses for recovery of the aggregation capacity of a reconstructed soil in a coal mining area in Southern Brazil. *Revista Brasileira de Ciência do Solo*. 2014;**38**:327-335 [Accessed date: August 23, 2022]
- [11] Barboza FD, Stumpf L, Pauletto EA, De Lima CLR, Pinto LFS, Jardim TM,

- et al. Impact of machine traffic events on the physical quality of a minesoil after topographic reconstruction. *Soil and Tillage Research*. 2021;**210**:104981 [Accesssed date: July 19, 2023]
- [12] Reis DA, Lima CLR, Pauletto EA. Resistência tênsil de agregados e compressibilidade de um solo construído com plantas de cobertura em área de mineração de carvão em Candiota. *Revista Brasileira de Ciência do Solo*. 2014;**38**:669-678 [Accesssed date: February 24, 2024]
- [13] Bitencourt DGB, Pinto LFS, Pauletto EA, Silva MT, Garcia GF. Geração de drenagem ácida e de contaminação por metais pesados em perfis de solos construídos em área de mineração de carvão. *Revista Brasileira de Ciência do Solo*. 2015;**39**:1-14 [Accesssed date: February 14, 2024]
- [14] Guadagnin CA, Pauletto EA, Pinto LFS. Taxa de infiltração estável da água ao longo de transeções em solos construídos na área de mineração de carvão de Candiota – RS. *Revista Brasileira de Agrociência, Pelotas*. 2007;**13**(3):337-342 [Accesssed date: February 14, 2024]
- [15] Guadagnin CA. Infiltração de água ao longo de uma transeção em solos construídos na área de mineração de carvão de Candiota – RS Dissertação (Mestrado em Ciências). Pelotas, 62 p: Programa de Pós-Graduação em Agronomia, área de concentração: Solos. Faculdade de Agronomia Eliseu Maciel, Universidade Federal de Pelotas; 2002 [Accesssed date: April 02, 2024]
- [16] Pinto LFS, Stumpf L, Miguel P, Dutra LA Jr, Leidemer JD, Barbosa LS, et al. Reclamation of soils degraded by surface coal mining. In: Soni A, editor. *Mining Techniques - Past, Present and Future*. IntechOpen; 2021. DOI: 10.5772/intechopen.79241 [Accesssed date: August 31, 2022]
- [17] Stumpf L, Pauletto EA, Pinto LFS, Geissler LO, Castilhos DD, Souza DL, et al. Biological and physical quality of a mined soil under revegetation with perennial grasses. *Revista Brasileira de Ciências Agrárias*. 2018;**13**(1):e5498. DOI: 10.5039/agraria.v13i1a5498 [Accesssed date: August 30, 2022]
- [18] Jardim TM, Geissler L, Pauletto EA, Morselli TBGA, Castilhos DD, Pinto LFS, et al. Fauna edáfica de um solo construído em área de mineração de carvão revegetado com diferentes espécies de Poáceas. In: *Anais do... V Cbcm – congresso brasileiro de carvão mineral*. Associação Brasileira de Carvão Mineral, Criciúma, SC, Brasil. De 29 de maio a 01 de junho. 2017 [Accesssed date: March 02, 2024]
- [19] Stumpf L, Pauletto EA, Pinto LFS, Ambus JV, Garcia GF, Silva TS. Características químicas de um solo construído e seus efeitos no desenvolvimento radicular de gramíneas perenes. *Revista Brasileira de Ciências Agrárias*. 2016;**11**(4):343-349 [Accesssed date: February 14, 2024]
- [20] Sanderman J, Hengl T, Fiske GJ. Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences*. 2017;**114**:9575-9580. DOI: 10.1073/pnas.1706103114 [Accesssed date: March 17, 2024]
- [21] Gregory AS, Ritz K, McGrath SP, Quinton JN, Goulding KWT, Jones RJA, et al. A review of the impacts of degradation threats on soil properties in the UK. *Soil Use and Management*. 2015;**31**(Suppl. 1):1-15. DOI: 10.1111/sum.12212 [Accesssed date: October 14, 2023]
- [22] Marques L. O decênio decisivo: propostas para uma política de sobrevivência. São Paulo: Elefante; 2023, 624 p

- [23] Dick DP, Hanke D. A matéria orgânica do solo: propriedades, reações e processos. In: Tiecher T, Silva LS, Martins AP, Mallmann FJK, editors. *Química do Solo*. Santa Maria: Sociedade Brasileira de Ciência do Solo – Núcleo Regional Sul; 2023. pp. 83-138, 320 p
- [24] Ruiz F, Safanelli JL, Perlatti F, Cherubin MR, Demattê JAM, Cerri CEP, et al. Constructing soils for climate-smart mining. *Communications Earth and Environment*. 2023;4:219. DOI: 10.1038/s43247-023-00862-x [Accessed date: October 12, 2023]
- [25] Ahirwal J, Kumar A, Pietrzykowski M, Maiti SK. Reclamation of coal mine spoil and its effect on technosol quality and carbon sequestration: A case study from India. *Environmental Science and Pollution Research*. 2018;25:27992-28003 [Accessed date: October 12, 2023]
- [26] Smith P. Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*. 2016;22:1315-1324. DOI: 10.1111/gcb.13178 [Accessed date: October 24, 2023]
- [27] Tripathi N, Singh RS, Nathanail CP. Mine spoil acts as a sink of carbon dioxide in Indian dry tropical environment. *Science of the Total Environment*. 2014;468-469:1162-1171. DOI: 10.1016/j.scitotenv.2013.09.024 [Accessed date: April 11, 2024]
- [28] Ussiri DAN, Lal R. Carbon sequestration in reclaimed minesoils. *Critical Reviews in Plant Sciences*. 2005;24(3):151-165. DOI: 10.1080/07352680591002147 [Accessed date: October 11, 2023]
- [29] Shrestha RK, Lal R. Carbon and nitrogen pools in reclaimed land under forestland pasture ecosystems in Ohio, USA. *Geoderma*. 2010;157:196-205. DOI: 10.1016/j.geoderma.2010.04.013 [Accessed date: April 26, 2024]
- [30] Ferreira TO, Ruiz F, Queiroz HM, Otero XL, Cherubin MR, Lopes TA, et al. Tecnossolos: da pedogênes às aplicações ambientais. In: Nogueira TAR, Cherubin MR, Pereira APA, Tiecher T, editors. *Tópicos em Ciência do Solo*. Vol. 12. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2023. pp. 290-316, 466 p
- [31] Cerri CEP, Abbruzzini CBB, Durigan MR, Freitas RCA, Lisboa IP, Oliveira DMS, et al. Estoques de carbono e fluxo de gases de efeito estufa em agrossistemas no Brasil. In: Nascimento CWA, Souza VS Jr, Freire MBGS, Souza ER, editors. *Tópicos em Ciência do Solo*. Vol. 9. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2015. pp. 1-47, 290 p
- [32] Köppen W. *Climatologia: con un estudio de los climas de la tierra*. México: Fondo de Cultura Económica; 1948. 479 p
- [33] Inmet – Instituto Nacional De Meteorologia. Normais climatológicas do Brasil – Período de 1961-2020. Estação Fluviométrica n. 83.980, Bagé, RS. Disponível em: <https://portal.inmet.gov.br/normais> [Accessed date: October 11, 2023]
- [34] Thornthwaite CW, Mather JR. *The Water Balance*. Vol. 8(1). Centerton, NJ: Drexel Institute of Technology - Laboratory of Climatology. Publications in Climatology; 1955. 104 p
- [35] Companhia Riograndense De Mineração - CRM. Balanço patrimonial do exercício. 2021. Available from: <https://crm.rs.gov.br/upload/arquivos/202205/02104808-balanco-2021.pdf> [Accessed date: February 15, 2023]
- [36] Holanda-Neto MR. Atributos microbiológicos de um solo construído vegetado com gramíneas após mineração

de carvão em Candiota/RS (Dissertação Mestrado em Ciências). Brasil: Programa de Pós-Graduação em Agronomia. Faculdade de Agronomia Eliseu Maciel, Universidade Federal de Pelotas; 2011, 96 p [Accessed date: April 02, 2024]

[37] Geissler LO. Atributos físico-químicos e da fauna edáfica como indicadores de recuperação de áreas degradadas pela mineração de carvão (Dissertação Mestrado em Ciências). Pelotas: Programa de Pós-graduação em Manejo e Conservação do Solo e da Água, Universidade Federal de Pelotas, Faculdade de Agronomia Eliseu Maciel, Depto de Solos; 2016, 94 p [Accessed date: February 10, 2024]

[38] Castro RC. Avaliação temporal de atributos físicos de um solo construído em área de mineração de carvão recuperado com gramíneas perenes (Dissertação Mestrado em Ciências). Pelotas, RS: Programa de Pós-graduação em Agronomia, Universidade Federal de Pelotas, Faculdade de Agronomia Eliseu Maciel, Depto de Solos; 2012. 99 p [Accessed date: February 24, 2024]

[39] Franco AMP. Caracterização física de um solo construídos na área de mineração de carvão de Candiota, RS. (Dissertação Mestrado em Ciências). Pelotas, RS: Programa de Pós-graduação em Agronomia, Universidade Federal de Pelotas, Faculdade de Agronomia Eliseu Maciel, Depto de Solos; 2006, 120 p [Accessed date: February 15, 2024]

[40] Gonçalves FC. Efeito de plantas de cobertura sobre os atributos físicos de um solo construído na área de mineração de carvão de Candiota, RS após três anos. Pelotas, RS (Dissertação Mestrado em Ciências). Pelotas: Programa de Pós-graduação em Manejo e Conservação do Solo e da Água, Faculdade de Agronomia Eliseu Maciel, Universidade Federal de Pelotas; 2008, 91 p [Accessed date: February 14, 2024]

[41] Rodrigues MF. Avaliação da recuperação da estrutura de um solo construído em áreas de mineração de carvão utilizando um método visual (Dissertação Mestrado em Ciências). Pelotas, RS: Programa de Pós-Graduação em Manejo e Conservação do Solo e da Água - Universidade Federal de Pelotas; 2010. 66 p [Accessed date: April 12, 2024]

[42] Cook BG, Pengelly BC, Schultze-Kraft R, Taylor M, Burkart S, Cardoso Arango JA, et al. Tropical Forages: An Interactive Selection Tool. 2nd and Revised ed. Nairobi, Kenya: International Center for Tropical Agriculture (CIAT), Cali, Colombia and International Livestock Research Institute (ILRI); 2020. Available from: www.tropicalforages.info [Accessed date: February 23, 2023]

[43] Machado AA. Sistema de análise estatística para Windows (WINSTAT). Pelotas, RS: Universidade Federal de Pelotas, CD; 2001

[44] Montgomery DC, Runger GC. Estatística aplicada e probabilidade para engenheiros. 6ª ed. Rio de Janeiro: LTC; 2018. 629 p

[45] Devore JL. Probabilidade e estatística para engenharia e ciências. São Paulo: Cengage Learning; 2016. 693 p

[46] Fernandes FA, Fernandes AHBM. Cálculo dos estoques de carbono do solo sob diferentes condições de manejo. Vol. 69. Corumbá: Embrapa Pantanal. (Embrapa Pantanal. Comunicado Técnico); 2009. 4 p. Disponível em: http://www.cpap.embrapa.br/publicacoes/download.php?arq_pdf=COT69 [Accessed date: April 10, 2024]

[47] Sociedade Brasileira De Ciência Do Solo. Manual de adubação e de calagem para os Estados do Rio Grande do Sul e de Santa Catarina. 10ª ed. Porto Alegre:

Sociedade Brasileira de Ciência do Solo. Comissão de Química e Fertilidade do Solo, 2004, 400 p

[48] Berthelin J, Laba M, Lemaire G, Powlson D, Tessier D, Wander M, et al. Soil carbon sequestration for climate change mitigation: Mineralization kinetics of organic inputs as an overlooked limitation. *European Journal of Soil Science*. 2022, 9 p;73:e13221. DOI: 10.1111/ejss.13221 [Accessed date: November 25, 2023]

[49] Li J, Xin Z, Yan J, Li H, Chen J, Ding G. Physicochemical and microbiological assessment of soil quality on a chronosequence of a mine reclamation site. *European Journal of Soil Science*. 2018;69:1056-1067. DOI: 10.1111/ejss.12714 [Accessed date: April 10, 2024]

[50] Li X, Lei S, Liu F, Wang W. Analysis of plant and soil restoration process and degree of refuse dumps in open-pit coal mining areas. *International Journal of Environmental Research and Public Health*. 2020;17:1975. DOI: 10.3390/ijerph17061975 [Accessed date: November 23, 2023]

[51] Beylich A, Oberholzer HR, Stefan Schrader S, Heinrich Höper H, Wilke BM. Evaluation of soil compaction effects on soil biota and soil biological processes in soils. *Soil and Tillage Research*. 2010;109:133-143. DOI: 10.1016/j.still.2010.05.010 [Accessed date: October 14, 2023]

[52] Feng Y, Wang JM, Bai ZK, Reading L. Effects of surface coal mining and land reclamation on soil properties: A review. *Earth Science Reviews*. 2019;191:12-25. DOI: 10.1016/j.earscirev.2019.02.015 [Accessed date: July 19, 2023]

[53] Wang S, Cao Y, Pietrzykowski M, Zhou W, Zhao Z, Bai Z. Spatial distribution of soil bulk density and its

relationship with slope and vegetation allocation model in rehabilitation of dumping site in loess open-pit mine area. *Environmental Monitoring and Assessment*. 2020;192:1-18 [Accessed date: October 11, 2023]

[54] Mukhopadhyay S, Maiti SK, Masto RE. Development of mine soil quality index (MSQI) for evaluation of reclamation success: A chronosequence study. *Ecological Engineering*. 2014;71:10-20. DOI: 10.1016/j.ecoleng.2014.07.001 [Accessed date: April 11, 2024]

[55] Fernandez MBG, Stumpf L, Miguel P, Pinto LFS, Carlos FS, Schubert RN, et al. Biological quality and organic matter dynamics in minesoil at 18 years reclamation with perennial grasses. *Ecological Engineering*. 2023;187:106866. DOI: 10.1016/j.ecoleng.2022.106866 [Accessed date: July 19, 2023]

[56] Silva RA. Estatística decodificada. São Paulo: Blucher; 2023. 418 p