

CARBON STOCKS IN MINED AREA RECLAIMED BY LEGUMINOUS TREES AND SLUDGE¹

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ABSTRACT – Few studies have been carried out on aboveground (or belowground) and soil/substrate C accumulation in severely degraded areas, such as mined areas. The present study was developed in order to find a recovery strategy for a mined area and characterize its potential for C sequestration by planting two nitrogen-fixing Brazilian tree species (*Mimosa caesalpinifolia* Benth and *M. bimucronata* (DC.) O. Kuntze). Sewage sludge was included in the experimental design. An experiment under randomized block condition and 2 x 5 factorial design with four replications were defined and carried out, in Rio de Janeiro State, Brazil. The treatments consisted of a combination of both tree species and five sewage sludge doses (0, 2.85; 5.70; 11.40 and 22.80 Mg ha⁻¹). *M. caesalpinifolia* grows better ($p < 0.05$) in reclaimed areas than *M. bimucronata*, even though neither the height nor the basal area of both species responded to the sludge application. Carbon stock in the tree trunks differ between species (27.3 and 14.3 Mg ha⁻¹, for *M. caesalpinifolia* and *M. bimucronata*, respectively), and was influenced by the doses of sewage sludge, whereas the soil carbon stock (0-10 cm) did not differ between species and doses (12.0 and 12.2 Mg ha⁻¹, for *M. caesalpinifolia* and *M. bimucronata*, respectively). Soil fertility in the degraded site was found to be improved by legume trees six years after planting, with a small influence of the sewage sludge level. Mined areas recovered with legume trees can sequester significant amounts of C both in aboveground biomass and soil in a short period of time.

Keywords: Soil carbon and nutrients accretion; Reclamation of soil; Aboveground biomass accumulation.

ESTOQUE DE CARBONO EM ÁREAS DE MINERAÇÃO RECUPERADA COM LEGUMINOSAS ARBÓREAS E LODO

RESUMO – Poucos estudos foram conduzidos em relação à acumulação de C na parte aérea (ou subterrânea) e solo/substrato em áreas severamente degradadas, como áreas mineradas. O presente estudo foi desenvolvido para encontrar uma estratégia de recuperação para uma área minerada e caracterizar o seu potencial de sequestro de C a partir do plantio de duas espécies de árvores brasileiras que fixam nitrogênio do ar (*Mimosa caesalpinifolia* Benth e *M. bimucronata* (DC) O. Kuntze). Lodo de esgoto foi incluído no desenho experimental. Assim, um experimento em delineamento em blocos ao acaso e esquema fatorial 2 x 5 e quatro repetições foi instalado no estado do Rio de Janeiro, Brasil. Os tratamentos consistiram em uma combinação de duas espécies arbóreas e cinco doses de lodo de esgoto (0, 2,85; 5,70; 11,40 e 22,80 Mg ha⁻¹). *M. caesalpinifolia* cresceu melhor ($p < 0,05$) na área recuperada do que *M. bimucronata*, mesmo que nem a altura, nem a área basal de ambas as espécies tenham respondido à aplicação do lodo. O estoque de carbono nos troncos das árvores diferiu entre as espécies (27,3 e 14,3 Mg ha⁻¹, para *M. caesalpinifolia* e *M. bimucronata*, respectivamente) e foi influenciado pelas doses de lodo de esgoto, enquanto o estoque de carbono do solo (0-10 cm) não diferiu entre espécies e doses (12,0 e 12,2 Mg ha⁻¹, para *M. caesalpinifolia* e *M. bimucronata*, respectivamente). A fertilidade do solo no local degradado foi melhorada pelas leguminosas, seis anos após o plantio, com uma pequena influência do lodo de esgoto. Áreas mineradas recuperadas com leguminosas podem sequestrar quantidades significativas de C, tanto na biomassa aérea quanto no solo em um curto período de tempo.

Palavras-Chave: Acréscimo de carbono e nutrientes do solo; Recuperação de solos; Acúmulo de biomassa da parte aérea.

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1 INTRODUCTION

In severely degraded lands, such as mining areas, the loss of local “ecological memory” (Bengtsson et al., 2003) may result in high rehabilitation costs, since ecological memory is suggested to hamper the natural development of either simple or complex vegetation communities (Silva et al., 2013). On the other hand, the period after rehabilitation intervention is an important factor for the return of key properties to both degraded soil and vegetation structure (Parrotta and Knowles, 1999; Balieiro et al., 2008; Reis, 2006; Banning et al., 2008; Chaudhuri et al., 2013; Wick et al., 2013). However in some cases restoration of soil quality could occur faster than the vegetation community (Parrotta and Knowles, 1999; Silva et al., 2013). The selection and the number of species to be planted (Parrotta and Knowles, 1999; Rodrigues et al., 2009), the use of organic residues, conditioners (such as biosolid, ash or top soil), lime and/or fertilizers (Fortes, 2000; Bendfeldt et al., 2001; Reis, 2006; Shrestha and Lal, 2006; Wick et al., 2013; Silva et al., 2013) or even the planting method (direct seeding or use of seedlings) are factors that may accelerate biomass accumulation in different compartments of the recovering ecosystem, as well as soil C sequestration and the return of certain ecological soil functions (Camargo et al., 2002; Parrotta and Knowles, 2001; Reis, 2006; Banning et al., 2008; Kanowski and Catterall, 2010; Evans et al., 2013; Silva et al., 2013).

The use of fast growing N_2 -fixing legume trees in the rehabilitation of severely degraded lands has been considered an advantage by several researchers (Franco and Faria, 1997; Macedo et al., 2008; Yang et al., 2009; Wang et al., 2010; Chaer et al., 2011). Most of them have reported that the natural introduction of biologically fixed N can intensify nutrient cycling and stabilize soil organic matter in these environments, and hence improve the quality of the degraded substrate. A significant soil C stock (0-60cm: 88.1 Mg ha⁻¹) and a high rate (1.73 Mg ha⁻¹ year⁻¹) of storage of this element were found after 13 years of a reforestation using N_2 -fixing legumes (*Acacia mangium*, *A. auriculiformis*, *Enterolobium contortisilicquum*, *Gliciridia sepium*, *Leucena leucocephala*, *Mimosa caesalpinifolia* and *Paraseranthes falcataria*) in a reclaimed area aggravated by gully erosion (Macedo et al., 2008). On the other hand, depending on the quantity and quality of the material deposited on the soil, the benefits may not

be as good as expected (Parrotta and Knowles, 1999; Singh et al., 2006; Wang et al., 2010). Parrotta and Knowles (1999) reported that in areas of bauxite mining, while fast growing commercial tree species (*Eucalyptus camaldulensis*, *E. citriodora*, *E. pellita*, *E. torreliana*, *E. urophylla*, *Acacia mangium* and *Sclerobium paniculatum*) presented high growth and deposited significant amounts of litter on the substrate, the slow decomposition rate of these residues prevented the development of the organic horizon in bauxite waste tanks. Moreover, the authors mentioned that such recalcitrant organic material affected succession negatively, as the litter layer layer was suggested to physically avoid seed germination. Singh et al. (2006), who studied coal mines in India, Wang et al. (2010), who evaluated areas degraded by erosion in China, and Resende et al. (2006), who monitored reclaimed areas in southeastern Brazil, observed different soil C sequestration rates and soil fertility recovery (nutritional status), depending on the species planted, which corroborates the hypothesis that the species - even among legume trees - can have different effects on soil quality. Evaluating a 14-year restoration chronosequence in an opencast mine area, Silva et al. (2013) attributed soil C accumulation to the synergic effect of these resource inputs and the invasion of an exotic species. Using a multi-proxy approach, combining vegetation survey with the analysis of plant and soil isotopic abundance and chemical and physical fractionation of SOM, these authors observed a consistent increase of soil C:N, C:P and $\Delta^{15}N$ over time, reflecting the effects of invasive grasses controlling resource availability.

Few studies have been carried out in Brazil regarding the C accumulation capacity both in the aboveground and soil/substrate of severely degraded areas. We believed that by increasing tree growth and biomass return to the soil the ecosystems would increase its C sequestration capacity as well as its quality. The present study was developed in order to find a recovery strategy for a reclaimed area and to characterize its potential for C sequestration by planting two native Brazilian N_2 -fixing legume tree species, *Mimosa caesalpinifolia* Benth and *M. bimucronata* (DC.) O. Kuntze. Sewage sludge application was included in the experimental design. The hypothesis was that (i) the mined areas could sequester significant quantities of C both in aboveground biomass and soils, and (ii) the sludge would act as a source of nutrients and a soil conditioner as well, thus accelerating the nutrient

dynamics and the growth of planted species. This study aims to evaluate the growth and aboveground biomass production of two leguminous tree species, cited above, under mining areas and the ability of both species to modify soil fertility and C stocks.

2 MATERIAL AND METHODS

2.1 Site description

The experiment was carried out in an area of the Rio de Janeiro/Galeão-Antonio Carlos Jobim International Airport called "Jazida de Itacolomi", located at 22°48'49"S and 43°14'31"W, in Rio de Janeiro city, Brazil.

Regarding regional climatic characterization, the study area is located in the intertropical strip, between the mountains and the sea in the Southeast region, with a humid tropical climate characterized by two distinct seasons. According to the Köppen and Geiger climate classification, Rio de Janeiro city has an Am climate, with an average annual rainfall around 1,278 mm. July is the driest month (~55mm) and January is the rainiest (~149 mm). The annual temperature reaches an average of 23.2 °C. Local land use history has been detailed by Bezerra et al. (2006). In summary, three ha were degraded due to clay extraction for the construction of the second passenger terminal of the airport. Before exploitation, the area was covered with a Yellow latosol (Oxisol), with a C horizon ranging four to five meters deep. This type of soil originates from sandy clay sediments, and is characterized by low natural fertility, good drainage, and high permeability. Mining resulted in an exposed C horizon after the removal of a 10-meter soil layer, affecting local drainage network, soil physical, chemical and biological properties, and local biodiversity as well. When the exploitation ended, the area became a landfill for the disposal of refuse piles. Local land reclamation included the removal of the refuse from soil surface, soil systematization, the management of stormwater runoff, and finally, the planting of seedlings of *Mimosa caesalpiniiifolia* and *M. bimucronata*. There were no plants on the experimental area before seedling plantation. Table 1 shows data of soil fertility and texture prior to the experiment. These previous analyses were used as the baseline (reference) for the evaluation of treatment effects six years after planting, although they were not used in the statistical analysis.

2.2 Study design and sampling

In late January 2001 we began a study on the viability of recovering the mining area using both fast growing tree species (*Mimosa caesalpiniiifolia* and *Mimosa bimucronata*) and sewage sludge produced by the airport wastewater treatment plant. A 2 x 5 factorial experiment (under randomized block condition) with four replications was designed. Treatments consisted of a combination of two tree species inoculated with efficient nitrogen-fixing bacterial strains and four sludge doses (0, 2.85; 5.70; 11.40 and 22.80 Mg ha⁻¹). The sludge chemical composition is shown in Table 2.

Mimosa seedlings were planted in 0.30 x 0.30 x 0.30 m holes, with a 2.0 m x 2.0 m spacing of planting. The total area of each plot was 64 m² (16 plants treatment⁻¹). For seedling fertilization, 80 grams of rock phosphate and 30 grams of potassium phosphate were applied in each hole. Both fertilizer and sludge were mixed and incorporated to the hole when seedlings were planted. In June 2003 sludge application was repeated using the same dose of the first application. During the first half of 2007 a yard stick and a measuring tape were used to measure the height and circumference at breast height (CBH) of each tree of two of the four blocks. Both the diameter at breast height (DBH) and the basal area were calculated from the CBH data. Trees with the respective value closest to the mean value calculated were selected for cutting. Between July and August 2007, three trees from each treatment were cut in Block 1 and one individual from treatments 1 and 2 (control), 3 and 4 (mean dose), and 5 and 6 (maximum dose) in blocks 2 and 3, totaling 18 trees of each species. After the trees were cut, their parts (leaves, branches and trunks) were separated and weighed in the field for sampling. Since sampling was performed in the driest months, few leaves were found, and the identification of dead branches was difficult. All dead or living branches were then quantified without differing them. In the Soil, Water and Plant Analysis laboratory (LASP) of Embrapa Solos, they were dried at 65 °C to determine their total dry weight. Subsamples were ground to determine the C content by dry digestion in a Perkin Elmer elemental analyzer (model 2400CHNS/O). As bark from trunk samples was ground separately, only the carbon stock (Mg ha⁻¹) of the trunk and branches was estimated based on the dry biomass and C content values.

Table 1– Chemical and physical attributes (0-20cm) of substrate prior to the experiment (extracted from Bezerra et al., 2006).**Tabela 1** – Atributos químicos e físicos (0-20cm) do substrato antes da implantação do experimento (extraído de Bezerra et al., 2006).

Block	Depth cm	pH H ₂ O (1:2,5)	C g kg ⁻¹	N	Ca	Mg	Na	K	Al	P	Clay	Sand	Silt
1	(0-10)	7,2	1,7	0,4	701,4	130,3	25,3	46,9	0,0	0,3	260	499	241
2	(0-10)	7,3	2,1	0,2	641,3	90,2	29,9	54,7	0,0	1,1	280	547	173
3	(0-10)	7,9	2,9	1,3	641,3	90,2	11,5	37,2	0,0	3,0	220	590	190

Table 2 – Chemical composition of sewage sludge used in the experiment (Bezerra et al., 2006).**Tabela 2** – Composição química do lodo de esgoto usado no experimento (Bezerra et al., 2006).

Moisture	pH (H ₂ O)	Organic C	TotalN	C/N	P	K	Mg	Ca	Na
g kg ⁻¹	(1:2,5)	g kg ⁻¹	g kg ⁻¹		mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹
8,2	5,6	224,1	26,7	8,4	4,800	1,000	3,400	15,400	400
Fe	Al	B	Mn	Cu	Zn	Ni	Cr	Pb	Cd
mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹
19,200	13,100	70	200	362,7	1,543,3	39,2	72,7	185,3	3,1

In July 2007, litterfall was completely removed from soil surface, the recovered substrate was sampled in three small trenches per plot that had been dug with a mattock. Samples were carefully collected to represent the treatment adequately and later were sent for chemical characterization after being dried and sieved. Exchangeable nutrients: Ca²⁺, Mg²⁺ and Al³⁺ extracted by 1 M KCl; P and K by Mehlich-1 extractant (0.05 mol L⁻¹ in HCl in 0.0125 mol L⁻¹ H₂SO₄) and pH (soil:water 1:5); potential acidity: H+Al extracted with calcium acetate 1 N (pH 7), titrated with 0.0125 N NaOH, were analyzed according to Empresa Brasileira de Pesquisa Agropecuária (1997). Inductively coupled plasma (ICP) apparatus for Ca²⁺, Mg²⁺ and Al³⁺, flame emission for K and photocolometry for P were used for nutrient determination. The sum of bases cations (S) (Ca, Mg and K), effective cation exchange capacity (T), calculated as the sum of S+(H+Al) and the base saturation (S/T), also were calculated. After these soils were sampled, new samples (0-10cm) were also collected with a 100 cm³ Koppeck ring to determine soil density. Carbon stocks were calculated using the following equation:

$$E = (C \times \rho \times E)/10,$$

where E= soil C stock Mg ha⁻¹); C= soil C content (g kg⁻¹); ρ= bulk density (g cm⁻³); and E= soil layer thickness (cm). No correction for soil mass was made to calculate the stocks.

2.3 Statistical analysis

The effects of species and sludge doses, as well as the interaction of these factors, were tested using analysis of variance at a 5% level of probability. When dose factor significance was detected, regression adjustment was done to describe better the effects of doses. Data from the 11.40 Mg ha⁻¹ sludge dose were not used in the statistical analysis, as plant growth values at this dose did not match the trend observed in the other doses, which may suggest a possible error in the application of sewage sludge.

3 RESULTS

Legume species performance were found to be different for height (p<0.01) and basal area (p<0.05) values, but no effect of sludge levels was detected on those variables for either species (Figure 1). *M. caesalpinifolia* presented the highest height values for all sludge doses, with mean values of 7.6 m. *M. bimucronata* presented a mean height of 6.1 m.

Both biomass and C stock accumulated in the trunks and branches were found to be different between *Mimosa caesalpinifolia* and *Mimosa bimucronata* (p<0.05) (Table 3). However, the effect of sludge doses was detected only for their trunks. No significant interaction was found between sludge doses and species. *M. caesalpinifolia* had higher dry biomass for both branch and trunk (average values of 30.3 and 58.4 Mg ha⁻¹, respectively) than *M. bimucronata* (20.8 and 31.8 Mg ha⁻¹) regardless of the

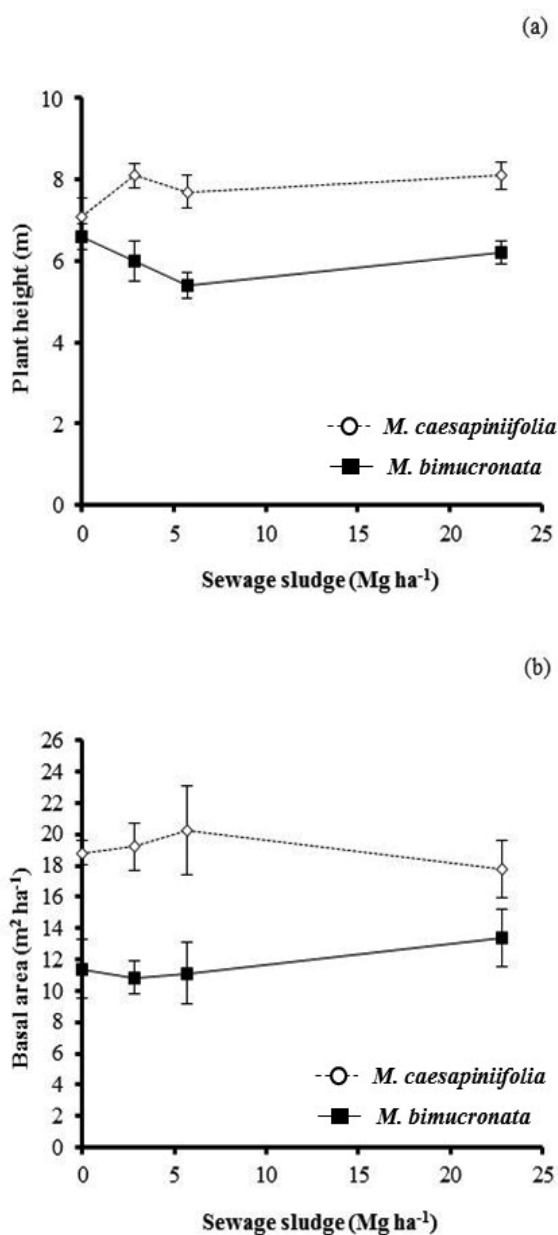


Figure 1 – Height (m) and basal area (m² ha⁻¹) of *Mimosa caesalpinifolia* Benth and *Mimosa bimucronata* (DC.) O. Kuntze, submitted to different sewage sludge doses six years after tree transplantation. Mean \pm standard deviation

Figura 1 – Altura (m) e área basal (m² ha⁻¹) de *Mimosa caesalpinifolia* Benth e *Mimosa bimucronata* (DC.) O. Kuntze, submetidos a diferentes doses de lodo de esgoto, aos 6 anos após transplântio. Média \pm desvio-padrão.

amount of sludge supplied. Biomass production accounted for species above-ground C stock (*M. caesalpinifolia* trunk, 27.3 Mg ha⁻¹; *M. bimucronata* trunk, 14.7 Mg ha⁻¹; *M. caesalpinifolia* branches, 14.1 Mg ha⁻¹ and *M. bimucronata* branches, 9.9 Mg ha⁻¹). C concentration mean values used to estimate C stocks for trunk and branches were very close (*M. Caesalpinifolia*, 46.8 \pm 0.4 g kg⁻¹, and 46.4 \pm 0.4 g kg⁻¹; *M. bimucronata* branches: 46.3 \pm 0.6 and 47.7 \pm 0.4 g kg⁻¹).

No significant differences were observed in the soil density due to the sludge dose. Similarly, the C stocks in the superficial soil layer (0-10 cm) did not differ between the *Mimosa caesalpinifolia* and *Mimosa bimucronata* plots or for the sludge doses. Six years after planting, the soil C stocks reached average values of 12.0 and 12.2 Mg ha⁻¹ for *M. caesalpinifolia* and *M. bimucronata*, respectively.

The application of different sludge doses did not significantly alter the chemical attributes associated to fertility (Table 4). On the other hand, legume trees themselves improve the substrate quality, as the nutritional status of the substrate improves in comparison to its quality before legume planting.

4. DISCUSSION

The Fabaceae is a huge family considered the third largest land plant family. It is the most common family found in tropical rainforests and in dry forests in the Americas and Africa (Burnham and Johnson, 2004). With a widespread distribution across the world and in Brazil, sometimes the introduction of nitrogen fixing tree representatives could not be imply in successful restoration practices. So, we attributed the behavior of *M. caesalpinifolia* and *M. bimucronata* studied to their origin, since the first is a native species of the Caatinga biome (a harsh environment for plant growth) and *M. bimucronata* is a native species of subtropical regions. As Rio de Janeiro has a hot and humid climate, *M. caesalpinifolia* found a better environment to grow, confirming what Bezerra et al. (2006) found when evaluated the experiment 210 days after planting.

The performance of *M. caesalpinifolia* in post-mining soils can be considered satisfactory (41.4 Mg ha⁻¹ after 6 years), since the rates of aboveground dry matter accumulation (Mg ha⁻¹ year⁻¹) were slightly higher than those reported by Baggio and Carpanezzi (1997) in Curitiba, Paraná (South region) and Moura et al. (2006) in Itambé, in the state of Pernambuco (Northeast

Table 3 – Dry biomass (Mg.ha⁻¹) of branches and trunks and respective C stocks (Mg.ha⁻¹, in parenthesis) of *Mimosa caesalpinifolia* Benth and *Mimosa bimucronata* (DC.) O. Kuntze, submitted to different sewage sludge doses.

Tabela 3 – Matéria seca da parte aérea (Mg.ha⁻¹) de galhos e troncos e respectivos estoques (entre parênteses, Mg.ha⁻¹) de *Mimosa caesalpinifolia* Benth e *Mimosa bimucronata* (DC.) O. Kuntze, submetidas a diferentes doses de lodo de esgoto.

Sewage sludge doses Mg ha ⁻¹	Branches		Trunk		Total
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	<i>Mimosa caesalpinifolia</i>				
0	31.30 ± 14.86 ^a	(14.52)	43.67 ± 4.27	(20.44)	74.97 (34.96)
2.85	30.30 ± 9.32	(14.06)	65.45 ± 8.18	(30.63)	95.75 (44.69)
5.70	29.16 ± 11.55	(13.53)	59.48 ± 8.41	(27.83)	88.63 (41.36)
22.80	30.29 ± 7.54	(14.05)	64.85 ± 11.54	(30.35)	95.14 (44.40)
Average	30.26	(14.05)A	58.36	(27.31) A*	88.62 (41.35) A
	<i>Mimosa bimucronata</i>				
0	12.01 ± 8.2	(5.73)	25.07 ± 11.52	(11.61)	37.08 (17.34)
2.85	18.41 ± 1.64	(8.79)	21.30 ± 6.14	(9.87)	39.71 (18.65)
5.70	23.06 ± 10.33	(11.00)	41.04 ± 22.04	(19.01)	64.10 (30.01)
22.80	29.92 ± 14.63	(14.28)	39.64 ± 19.04	(18.36)	69.55 (32.64)
Average	20.85	(9.95)A	31.76	(14.71) B	52.61 (24.66) B

a. Mean ± standard deviation * Mean value followed different letter, in the same column, show significant difference in the Tukey test (5% probability);

Table 4 – Substrate fertility (0-10cm) at the end of the experiment. Mean values ± standard deviation (in parentheses)

Tabela 4 – Fertilidade do substrato (0-10cm) ao final do experimento. Valores médios dos atributos ± desvio-padrão (entre parênteses)

Doses	Species	pH H ₂ O ^a	Al ^b	Ca ^b	Mg ^b	K ^c	H + Al ^d	P ^e	S ^e	T ^f	V ^g	C ^h
		(1:2.5)	— cmol _c dm ⁻³ —				cmol _c dm ⁻³	mg. dm ⁻³	cmol _c dm ⁻³	%	g/kg	
0	<i>M. caesalpinifolia</i>	7.1 (0.6)	0.0 (0.0)	4.6 (0.2)	0.7 (0.0)	106.3 (39.2)	0.5 (1.0)	26.6 (16.3)	5.7 (0.3)	6.2 (0.8)	93.3 (13.5)	8.7 (0.4)
	<i>M. bimucronata</i>	7.7 (0.6)	0.0 (0.0)	4.8 (1.6)	0.8 (0.1)	92.5 (38.0)	0.2 (0.4)	20.7 (17.3)	5.8 (1.7)	6.0 (1.4)	95.8 (8.5)	7.4 (1.5)
2.85	<i>M. caesalpinifolia</i>	7.6 (0.6)	0.0 (0.0)	4.6 (1.6)	0.8 (0.2)	107.3 (28.0)	0.0 (0.0)	15.1 (11.0)	5.7 (1.6)	5.7 (1.6)	100.0 (0.0)	7.7 (1.8)
	<i>M. bimucronata</i>	6.9 (1.4)	0.0 (0.1)	3.7 (2.0)	1.0 (0.4)	104.3 (33.7)	0.5 (1.1)	9.4 (9.4)	5.0 (2.2)	5.5 (1.5)	88.3 (23.5)	7.0 (1.7)
5.7	<i>M. caesalpinifolia</i>	6.2 (1.2)	0.1 (0.2)	2.9 (1.2)	0.9 (0.4)	81.8 (16.3)	1.3 (1.1)	12.8 (11.3)	4.1 (1.5)	5.3 (1.2)	75.5 (24.4)	7.4 (2.2)
	<i>M. bimucronata</i>	6.4 (1.2)	0.0 (0.0)	3.0 (1.3)	0.9 (0.1)	103.3 (14.4)	0.8 (1.0)	15.3 (15.1)	4.1 (1.3)	4.9 (0.7)	83.0 (21.0)	6.8 (1.8)
22.8	<i>M. caesalpinifolia</i>	7.2 (0.7)	0.0 (0.0)	4.5 (2.0)	0.9 (0.5)	95.5 (16.9)	0.3 (0.7)	12.3 (5.2)	5.7 (2.5)	6.1 (2.2)	93.5 (13.0)	6.0 (2.3)
	<i>M. bimucronata</i>	7.4 (0.5)	0.0 (0.0)	4.1 (0.6)	0.8 (0.3)	93.8 (56.0)	0.2 (0.4)	27.1 (17.4)	5.2 (0.3)	5.4 (0.5)	96.5 (7.0)	8.2 (3.1)

^a: pH (soil:water, 1:5); ^b: Exchangeable nutrients: Ca²⁺, Mg²⁺ and Al³⁺ extracted by 1 M KCl; ^c: P and K by Mehlich-1 extractant (0.05 mol L⁻¹ in HCl in 0,0125 mol L⁻¹ H₂SO₄); ^d: potential acidity; H+Al extracted with calcium acetate 1 N (pH 7), titrated with 0.0125 N NaOH; ^e: (S) Sum of bases cations: Ca, Mg and K; ^f: effective cation exchange capacity (T), calculated by sum of S+(H+Al) and ^g: base saturation (S/T)x100); ^hC: total organic carbon (dry combustion)

region), in undisturbed areas. On the other hand, *M. bimucronata* showed a worse performance in the present study (24.6 Mg ha⁻¹) than others reported by Fortes (2000), who evaluated several native and exotic species (*Acacia mangium*, *Mimosa caesalpinifolia* (*M. caesalpinifolia*), *Mimosa acutistipula*, *Prosopis juliflora*, *Leucaena leucocephala*) under bauxite mine soil mixed with alkaline ash exposure.

A high spatial variability of soil attributes was responsible for the lack of statistic difference among the treatments and this was corroborated by Banning et al. (2008) and Nyamadzawo et al. (2008). According

to Nyamadzawo et al. (2008) on minesoils and unmined sites there is an increase in sample variance over increasing amount of time, especially for some soil properties. The coefficient of variation (CV) for bulk density was lower, <15% percent at each site and depth, while for total C concentration and stocks, CV was high, 35 percent across all mined soils, and generally increased with depth.

Despite the differences in growth and carbon aboveground accumulation, no differences were found between species and sludge doses for soil carbon stocks. In addition, the values found (~12 Mg ha⁻¹) were lower

than those reported by Macedo et al. (2008) in sites reclaimed by planting legume trees (21.5 Mg ha^{-1}). Nevertheless, differences in plantation ages (six years for the Itacolomi site vs. 13 for the Angra dos Reis area), in the number of species planted, and even in the local site resilience in Angra dos Reis due to the close proximity to a significant Atlantic Forest remnant (Ribeiro et al., 2009), that improve the successional process could also justify these differences. The higher presence of grasses under the sites studied by Macedo et al. (2008) in comparison with our work corroborates the results of Silva et al. (2013) who observed a synergistic unprecedented carbon accumulation in an open-cast mine area effects of resources input (biosolid: tertiary-treatment domestic sewage sludge) and plant species invasion of grasses under 14-year restoration chronosequence (Silva et al., 2013). Bendfeldt et al. (2001) discuss that it is reasonable that a new pattern of aboveground and belowground interactions may result in C accumulation in degraded substrates. These authors reported that 16 years after applying different soil conditioners (topsoil, sawdust, municipal sewage sludge – 22, 56, 112 and 224 Mg ha^{-1}), C stocks had accumulated up to 8–10 Mg ha^{-1} in 1m-deep base layer of 2:1 sandstone to siltstone overburden material, for all treatments.

Using the C stocks (3.5 Mg ha^{-1}) from 2001 (year of experiment installation) as baseline (C data from Bezerra et al., 2006 and bulk density from our work), the rate of C sequestration for the first 6 years of reclaimed mine was estimated at $1.44 \text{ Mg ha}^{-1} \text{ year}^{-1}$, a figure that corroborates several authors (Wick et al., 2013: $1.27\text{--}2.00 \text{ Mg ha}^{-1} \text{ year}^{-1}$; Shrestha and Lal, 2006: $0.7\text{--}4.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$; Macedo et al., 2008: $1.73 \text{ Mg ha}^{-1} \text{ year}^{-1}$) for different reclaimed soils.

As observed in carbon stocks, different sludge doses did not change chemical attributes significantly after six years of planting. Although there were no significant interspecies differences, a lowered pH substrate detected after 180 days of planting the legume species (Bezerra et al., 2006) was still observed — slightly higher for *M. caesalpinifolia*. Despite the local applications, the sludge doses caused significant pH alterations and the regression models tested for each species did not allow good adjustments. Even though the literature widely states that atmospheric N_2 fixing legume species can reduce soil pH (Raven et al., 1990; Wang et al., 2010), other factors, such as litterfall decomposition, soil

respiration, cations uptake by legumes, or their spread by leaching, as well as the influence of atmospheric deposition, can favor soil pH reduction (Binkley and Giardina, 1997; Yamashita et al., 2008).

On the other hand, the average Ca and Mg content (all doses) in soil under both *M. caesalpinifolia* (4.14 and $0.83 \text{ cmol}_c \text{ dm}^{-3}$) and *M. bimucronata* (3.88 and $0.83 \text{ cmol}_c \text{ dm}^{-3}$) were found to be higher six years after planting. Considering that the sludge levels had no effects when applied in the planting holes, it could suggest that fertilization itself plus plant growth were enough to trigger local biogeochemical cycling.

A great improvement in K levels in the superficial soil layer sampled was observed, with levels approximately 50% higher than those detected by Bezerra et al. (2006). Considering that the K content was high before planting, and the high mobility of this nutrient in plants, it can be inferred that it was intensely and efficiently recycled during the study period. As cited before, the natural seasonal fall of leaves may have accounted for a great biomass accumulation on soil surface. Phosphorus was the only soil attribute that was significantly affected by the sludge doses, even though the regression models tested for each species did not allow good adjustments. This result could be explained by the fact that organic and humic substances in the sludge may have increased phosphate uptake by the plants, given that they can block phosphate adsorption sites of oxides and hydroxides of Fe and Al from the substrate — not only at the hole level but also for plot level (Sibanda and Young, 1986; Hua et al., 2008; Rocha et al., 2015). The increase in C concentration and stocks appears to modulate the phosphorus dynamic in this degraded area. Efforts in terms of studies are recommended in this direction as C (and N) contents in soils could increase in detriment of P availability, depending on the mixture and structure of the forest planted (Kaye et al., 2000; Koutika et al., 2014).

After six years the successive process of planting had begun, the species *Panicum maximum* (Colonião grass) and some *Leucaena leucocephala* (leucena) plants were dispersed in all plots. The grass was dominated by the trees planted, while leucaena reached the same size as them. With low representatives in terms of number and biomass, we believed that the contribution of both species for soil C stocks estimations was also low, as well as their contribution for the aboveground biomass.

5 CONCLUSION

The *M. caesalpiniiifolia* was found to grow better in reclaimed areas than *M. bimucronata*, even though neither the height nor the basal area of either species responded to the sludge levels tested. On other hand the carbon stocked in the tree trunks was affected by the doses of sewer sludge applied, whereas the soil carbon stock was not. The degraded substrate fertility was improved by the revegetation strategy, although no significant differences were observed between the treatments after six years for any attribute, except phosphorus availability, which was affected by sludge levels. Finally, we concluded reclaimed areas revegetated with leguminous trees can stock significant amounts of C, in both aboveground biomass and soil, in a short course of time.

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