SOIL C AND N STOCKS IN BAUXITE-MINED AREAS UNDER REHABILITATION WITH FOREST SPECIES

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Abstract

Forest cover can be effective in reducing the changes caused by mining, especially through the recovery of organic matter stocks. The objective was to evaluate the C and N stocks in fractions of soil organic matter in bauxite-mined area under rehabilitation with forest species. The forest covers evaluated were: eucalyptus (Euc), A. peregrina (Ap) and a mixed planting of native forest species (Nat), in addition to an area without forest cover (WCov) and native forest in an unmined area (NV). The fertilization treatments studied were a standard adopted by the company (SF), organic fertilizer (OF), chemical fertilizer (CF) and OF + CF. The total stocks of C and N from particulate organic matter (POM), mineral-associated organic matter (MOM), microbial biomass (MB) and labile C (LC) were estimated, as well as the C/N ratio and the carbon management index (CMI). The influence of the presence or absence of litter was evaluated, as well as the roots on C and N stocks in the soil. The stocks of total and labile C, CMI and MBC did not differ between the forest covers studied in the 0-60 cm layer, being lower than those in NV and higher than those found in WCov. The other variables (TN, CMOM, NMOM, CPOM, NPOM and MBN) were higher only in the NV. Mining causes reduction of organic matter fractions; however, forest cover increase the stocks of TOC, LC and CMI. Roots are more associated with the recovery of C and N stocks than litter and trunk biomass.

1. INTRODUCTION

Mining is one of the anthropic activities that most impact the soil, causing major interferences in its physical, chemical and biological properties. Rehabilitation of these mined areas requires efforts by the companies in the sector, environmental agencies, universities and research institutions that seek effective procedures to reestablish the essential processes of the degraded soil and ecosystems (Carneiro et al., 2008).

Soil organic matter (SOM) is one of the main agents of formation and stabilization of soil aggregates, so alterations in land use and adoption of management practices that promote breakage of aggregates lead to exposure of SOM and consequent microbiological degradation (Ramesh et al., 2019). These conditions result in decrease of soil organic C (Matos et al., 2008), especially of more labile fractions of SOM, characterized by being more accessible to microbial action, i.e., more dynamic, responding faster to the impacts of the change caused by land use and management (Haynes, 2000; Passos et al., 2007).

Mining activities cause high SOM loss, especially due to increased mineralization with the fragmentation of aggregates during removal, storage and return of the surface layer, erosion, reduction or absence of biomass (Lorenz & Lal, 2007; Shrestha & Lal, 2006; Tripathi, Singh & Nathanail, 2014) and mixture of surface and subsurface layers in these mined soils (Schwenke, Mulligan & Bell, 2000; Ward, 2000) in the procedures of rehabilitation of mined areas.

SOM can be considered a good indicator of soil quality in these areas under rehabilitation (Vilas Boas et al., 2018; Borges et al., 2019). Among the SOM fractions, labile C (LC) has been used as sensitive indicator of soil quality and particulate organic matter (POM) (Cambardella & Elliott, 1992; Lehmann, Cravo & Zech, 2001; Heyn et al., 2019; Figuerêdo et al., 2020), enabling the detection of changes caused by use, especially in a shorter period of time (Heyn et al., 2019). In addition, C and N stocks of microbial biomass can be good indicators, as they are easily altered by changes in land use (Li et al., 2018). Despite representing a small part of soil organic C, the microbiological properties of the soil have been considered sensitive indicators of alterations caused by the different land use and management systems (Araújo et al, 2013; Gama-Rodrigues et al., 2008; Huang et al., 2014; Silva et al., 2010). Among the microbiological indicators, microbial biomass represents the labile fraction of SOM, with dynamic nature, responding rapidly to interventions in soil management (Barreto et al., 2008).

Programs of rehabilitation of mined soils aim at improving their physical, chemical and biological attributes, which can be achieved with forest covers, favoring the increase in organic matter, biological N fixation, exploitation of nutrients, all at greater depths, as well as increase in water infiltration and storage, reduction in the loss of nutrients by erosion or leaching (Singh, Raghubanshi & Singh, 2004), etc. Although the importance of TOC, TN and their fractions in the soil is already well known, there are few studies on these attributes in areas that had been mined or are under rehabilitation, especially when exploited for bauxite (Vilas Boas et al., 2018; Borges et al., 2019), an environment that is pedogenetically well developed and characterized by the poverty in nutrients that are essential for plant development.

In this context, the objective of the present study was to evaluate the recovery of C and N stocks by soil organic matter fractions in bauxite-mined area through forest covers with native and exotic species cultivated under different sources of fertilization.

2. MATERIAL AND METHODS

2.1. Study area characterization and experimental design

The study was conducted in a rural property of the municipality of São Sebastião da Vargem Alegre, *Zona da Mata* region of Minas Gerais, Brazil (21°1´58´´S and 42°35´8´´W), at 780 m of altitude, in an area that had been under bauxite extraction by *Companhia Brasileira de Alumínio – Votorantim Metais* . The climate of the region is Cwa, according to Köppen's classification, with hot and rainy summers and well defined dry season, with average annual precipitation and temperature of 1,287 mm and 20.3 ºC, respectively (INMET, 2016). The soils were classified as *Latossolo Vermelho Amarelo distrófico típico* (Santos et al., 2013), which corresponds to an Oxisol (SOIL SURVEY STAFF, 2014). After mining activities, the surface layers (0-20 cm), stored for approximately one year, were returned to the original area during the process of topographic reconfiguration, followed by decompaction with subsoiler to 60 cm depth.

The area was mined for bauxite and reconfigured in 2009 and 2010, respectively. The experiment was installed in March 2011, using a randomized block design with split plots and three replicates. Plots with dimensions of 40 x 18 m were composed of the following forest covers: clonal eucalyptus (hybrid from crossing between *Eucalyptus urophylla* x *Eucalyptus grandis;* clone AEC144®) (Euc), 'angico vermelho' (*Anadenanthera peregrina* (L.) Speg) (Ap) and a mixed planting (Nat) composed of 16 native forest species of the region, namely: 'Angico vermelho' (*Anadenanthera peregrina* (L.) Speg) – Ap, 'Figueira' (*Ficus insipida* Willd) - Fi, 'Ingá cipó' (*Inga edulis* Mart.) – Ie, 'Jacaré' (*Piptadenia gonoacantha* (Mart.) JF Macbr.) – Pg, 'Orelha de negro' (*Enterolobium contortisiliquum* (Vell.) Morong.) - Ec, 'Paineira' (*Ceiba speciosa* (A. St. Hil.) Ravenna) – Cs, 'Saboneteira' (*Sapindus saponaria* L.) - Ss and 'Tamanqueira' (*Pera glabrata* (Schott) Poepp. Ex Baill.) – Pg, forest species that are considered pioneer. Non-pioneer species were: 'catiguá' (*Trichilia sp*) – Tsp, 'Camboatá' (*Cupania oblongifolia* Mart.) – Co, 'Garapa' (*Apuleia leiocarpa* (Vogel) JF Macbr.) - Al, 'Ipê tabaco' (*Handroanthus chrysotrichus* (Mart. Ex A. DC.) Mattos) – Hc, 'Jatobá' (*Hymenaea courbaril* var. *stilbocarpa* (Hayne) YT Lee & Langenh) – Hcs, 'Jequitibá' (*Lecythis sp*) – J2, 'Pau brasil' (*Paubrasilia echinata* Lam.) – Pe and 'Araticum' (*Annona squamosa* L.) – As. These native species were planted following the Quincunx model (4 pioneers and one climax in the center), at 2 x 1.5 m spacing, using seedlings produced from seeds collected in fragments of Atlantic Forest close to the study region. The spacing adopted for eucalyptus and *A. peregrina* in sole cropping was 3 x 2 m.

The subplots (10 × 18 m) included the standard fertilization used by the company (SF) in its rehabilitation activities of mined areas, with the propositions under study, which considered the SF and organic fertilization (OF), chemical fertilization (CF), and a combination of OF+CF. Six months before planting the trees, SF composed of 2.0 t ha^{-1} dolomitic limestone and 30.0 t ha^{-1} poultry litter (fresh, with an average of 30% moisture) was applied over the whole area; OF was composed of SF and 30 t ha^{-1} poultry litter, and CF included the application of a further 3 t ha^{-1} dolomitic limestone and 0.75 t ha^{-1} Bayovar natural reactive phosphate for Euc and Ap, and 1.5 t ha^{-1} for Nat. The application of OF+CF was a combination of the two supplementary applications (OF and CF). Part of the dose of poultry litter and limestone was applied to the planting hole and part between the rows, in this case, incorporated into the 0.00-0.15 m layer 30 days before planting, so that all plants received the same dose of fertilizer. The treatments with Euc and Ap received 22% of the dose of poultry litter in the planting hole and 78% between the rows, while the treatment with Nat received 44% in the planting hole and 56% between the rows. Similarly, the application of the limestone was carried out so that 25% of the total dose was applied to the holes and 75% between the rows for Euc and Ap; for Nat, 50% was applied to the planting hole and the remainder (50%) between the rows. The reactive natural phosphate was applied to the bottom of the planting holes.

In addition to the fertilization carried out at planting, the areas also received two doses of top-dressing fertilization, the first one month after setting up the experiment, consisting of 10 kg ha^{-1} of N, 22 kg ha^{-1} of P, and 8 kg ha^{-1} of K when planting Euc and Ap, and 20 kg ha^{-1} of N, 44 kg ha^{-1} of P, and 16 kg ha^{-1} of K when planting the multiple native species, enriched with micronutrients (1.7 kg ha^{-1} of B, 0.8 kg ha^{-1} of Zn, 0.8 kg ha^{-1} of Cu) for Euc and Ap, and double this dose for the native species, placed (in shallow holes) 0.20 m to the side of the plants. The second fertilization was carried out 10 months after starting the treatments, applying 67 kg ha^{-1} of N, 17 kg $ha^{-1}$of P, and 67 kg ha^{-1} of K to Euc and Ap, and 134 kg ha^{-1} of N, 34 kg ha^{-1} of P, and 134 kg ha^{-1} of K to Nat, in 0.05-m-deep grooves, in the upper part of the canopy projection area. It should be noted that only treatments with CF and OF+CF received the top-dressing fertilization, since this was carried out using chemical fertilizer only.

The main chemical and physical characteristics of the soil in the experimental area at the end of the evaluation period can be observed in the Attachment (Table S1)

2.2. Analysis of soil organic attributes

Soil samples from the 0-10, 10-20, 20-40 and 40-60 cm layers of each subplot, ground in mortar and passed through a 60-mesh sieve (0.250 mm), were used to determine the total organic C and total N (TOC and TN) and carbon and nitrogen from mineral-associated organic matter (CMOM and NMOM) and particulate organic matter (CPOM and NPOM) and of labile C (LC).

Organic carbon (C) was quantified by organic matter wet oxidation with 0.167 mol $L^{-1} K_2Cr_2O_7$ in sulfuric medium, using as energy source the heat released by H_2SO_4 and external heating source (YEOMANS; BREMNER, 1988). TN was determined by the Kjeldahl method, modified by Tedesco (1985), using sulfuric digestion, distillation and quantification by titration with 0.02 mol L^{-1} HCl. LC was extracted by oxidation in 0.33 mol $L^{-1} KMnO_4$ and quantified by molecular absorption spectrophotometry with reading of absorbance at 565 mm (BLAIR et al.,1995 modified by WEIL et al., 2003).

Physical fractionation of soil organic matter was performed by dispersing the soil with sodium hexametaphosphate (5 g L^{-1}) and horizontal shaking at 120 rpm. Subsequently, the samples were passed through a 170-mesh sieve (53 μm), which originated two fractions: retained fraction (particulate organic matter - POM) and the fraction that passed through the sieve (mineral-associated organic matter - MOM). These two fractions were dried in an oven at 60 ºC, weighed and passed through 100-mesh sieve (0.149 mm) to evaluate the contents of organic C and TN, according to Cambardella and Elliott (1992).

Microbial biomass carbon and nitrogen (MBC and MBN, respectively) of the soil were determined only in the 0-10 cm layer. Samples (<2 mm) were placed in plastic flasks with lids, incubated for 10 days at 25 °C, with moisture corresponding to 80% of moisture equivalent, in order to reestablish the microbial community. After incubation, MBC and MBN contents were determined by the irradiation-extraction method (ISLAM; WEIL, 1998), using a microwave oven. After irradiation, the samples were subjected to 0.5 mol $L^{-1}K_2SO_4$ extractor, and C in the extracts was quantified by wet oxidation without external heating and N by sulfuric digestion, followed by distillation and titration with HCL solution (TEDESCO et al., 1985).

The stocks of organic C and N of SOM fractions were calculated by multiplying the contents by the soil volume in each layer and by soil density under NV at the different depths (PULROLNIK et al., 2009).

Carbon management index (CMI) (BLAIR et al., 1995) was calculated from TOC, LC and non-labile organic C (NLC), based on the difference between TOC and LC, using the values obtained in the NV area as reference, through the following equation: $CMI = ((TOC_i/TOC_{NV})*((LC_i/NLC_i)/(LC_{NV}/NLC_{NV}))*100$, where TOC_i: total organic C of the area of i, where i = Euc, Ap, Nat or WCov; LC_i and NLC_i: labile and non-labile C, respectively, of i = Euc, Ap, Nat or WCov.

The influence of tree litter on soil C and N stocks and their fractions was evaluated by the presence and absence of litter in Euc, Ap and Nat, subjected to the fertilizations SF and OF+CF. Soil samples were collected below the litter collectors installed in the area to estimate the biomass supplied to the soil (data not presented in this study).

2.3. Root biomass and morphological attributes

Blocks of soil with dimensions of 20 x 20 x 20 cm were collected in triplicates in the interrows of Euc, Ap and Nat. After collection, roots were manually separated from the soil, washed and divided into two classes with diameter larger and smaller than 2 mm. After determining the wet weight, the roots were placed in plastic pots with 25% alcohol and stored in a refrigerator for later evaluation. An Epson XL 10000 scanner, equipped with additional light unit (TPU), and the software program WinRHIZO Pro 2009 were used to determine the following morphological characteristics: biomass of roots smaller than 2 mm (BioRSm2) and larger than 2 mm (BioRLg2), total root biomass (TotalRB), length of roots smaller than 2 mm (LengRSm2) and larger than 2 mm (LengRLg2), total root length (TotalRL), surface area of roots smaller than 2 mm (SARSm2) and larger than 2 mm (SARLg2), total surface area (TotalSA), and average diameter of roots smaller than 2 mm (DRSm2) and larger than 2 mm (DRLg2) and volume of roots smaller than 2 mm (VRSm2) and larger than 2 mm (VRLg2). After these evaluations, the roots were placed paper bags and dried in an oven at temperature of 60 °C to obtain the dry weight.

Besides the morphological characteristics determined, the percentages of roots smaller than 2 mm in relation to the total (PartBioRSm2), surface area of roots smaller than 2 mm in relation to the total surface area (PartSARSm2) and specific root length (SRL), that is, length of roots smaller than 2 mm in relation to the total root biomass.

2.4. Statistical analysis

The data were subjected to analysis of variance and the treatments were compared by Tukey test at 10% probability level, also considering the probability levels of 15% and 20% to discuss the tendencies exhibited by the studied treatments. In addition, the means of soil organic attributes and root morphological parameters were subjected to Pearson's correlation analysis ($p<0.1$, t test).

All statistical analyses were performed in the program Statistica 7.0.

3. RESULTS

The interaction between the types of fertilization and forest covers, in mined area after 56 months of planting, had no significant effect ($p>0.1$) on the evaluated organic attributes of the soil (Table S2). Because of these results, only the main effects of the forest covers and depths were addressed, considering the average of fertilizations (Table S3), which enabled the inclusion of the areas without cover (WCov) and of natural vegetation (NV) in the set of treatments as sources of variation in the statistical analysis.

The stocks of TOC, as well as those of TN, did not differ between the covers Euc, Ap, Nat and WCov at any of the depths evaluated, which did not occur when compared to NV ($p<0.1$), where the highest stocks were found (Table 1). Euc tended to show higher ($p<0.20$) TOC stocks compared to WCov in the 20-40 cm layer. However, when the entire profile was evaluated, that is, the 0-60 cm layer, lower values of TOC were found in the WCov area compared to Euc and Ap, but not differing from those of Nat. For TN, the soils of the Euc, Ap, Nat and WCov areas did not differ in terms of stocks in the 0-60 cm layer.

The C/N ratio showed significant differences in relation to the forest cover studied ($p<0.1$), which are due to Nat and WCov in the 40-60 cm layer, where the highest values were observed (Table 1). In the 0-60 cm layer, although NV tended to show the lowest C/N ratios ($p<0.15$), this difference was not confirmed at 10% probability when compared to the forest covers planted. There were differences only between WCov (highest C/N ratios) and NV.

Significant differences ($p<0.1$) were observed in LC stocks in the forest covers studied, with NV showing the highest stocks (Table 1). There was a trend ($p<0.15$) of the three forest covers planted to show higher LC contents in comparison to the area without cover. However, at 10% probability level, Euc, Ap and Nat were not statistically different from one other, as well as in relation to the WCov area, except for Euc, with higher LC stocks than the WCov area at 0-10 cm depth, which represented an increase of 850 kg ha^{-1}. For the other depths, in general, differences were observed only between NV and the other covers ($p<0.1$). The forest species planted after bauxite mining (Euc, Ap and Nat) increased LC stocks in comparison to the WCov area, when analyzing the sum of the 0-60 cm layer ($p<0.1$), with no difference between them.

The analysis of the results of soil CMI showed no significant differences ($p<0.1$) between the soils of the studied covers, at each depth, with all values lower than those of the NV reference. However, when the sum of all layers studied (0-60 cm) was evaluated, higher soil CMI was observed in the alternatives of rehabilitation compared to the WCov area, after 56 months of rehabilitation.

Insert Table 1

The results of C evaluations in the physical fractions of organic matter showed no differences between the forest covers planted and the WCov area for CMOM, as well as CPOM, ($p<0.1$), in the first two soil layers studied (0-10 and 10-20 cm) (Table 2). In these layers, NV had the highest stocks of CMOM and CPOM. In the 20-40 cm layer, Euc and Nat differed from the WCov area with the highest stocks of CMOM. For CPOM, the stocks were the same under all covers studied in the last two soil layers. Regarding the C fractions in the 0-60 cm layer, no significant differences were observed between the forest covers planted and the WCov area, with lower CMOM and CPOM stocks than those observed in NV.

In general, NMOM stocks were different among the studied covers ($p<0.1$), being higher in NV. In relation to the results of NPOM, of the studied cover, NV had the highest stocks ($p<0.1$) in the first two soil layers (0-10 and 10-20 cm). The forest covers planted and the WCov area did not differ as to the NMOM and NPOM stocks in the 0-60 cm layer, and the highest stocks were observed in NV.

The studied covers differ from one another in relation to MBC ($p<0.1$) (Table S5 and S6), and the WCov area had the lowest MBC stocks, while NV had the highest values (Table 3). The three forest covers Euc, Ap and Nat did not differ from one another and occupied an intermediate position between WCov and NV regarding the MBC stocks. For MBN, NV had the highest stocks ($p<0.1$), but Euc, Ap and Nat did not differ from the WCov area.

Insert Table 2

When the effects of presence or absence of litter on soil organic attributes were evaluated by ANOVA, there were no significant differences of interactions and main effects for any of the organic attributes studied.

The exception occurred with LC (Table S4), which was higher (1.55 t ha^{-1}, $p<0.1$) in the presence of litter, compared to its absence (1.33 t ha^{-1}).

Of the various root variables in the 0-20 cm layer, the values of biomass of roots smaller than 2 mm (BioRSm2), lengths of roots smaller than 2 mm (LengRSm2) and total root length (TotalRL) and the surface area of roots smaller than 2 mm (SARSm2) and total surface area (TotalSA) were high in NV, compared to other forest covers studied (Tukey, $p<0.1$; Table 3; Table S7). At this depth, there were cases in which NV was similar only to Nat for total root biomass (TotalRB), length of roots larger than 2 mm (LengRLg2) and volume of roots smaller than 2 mm (VRSm2) and larger than 2 mm (VRLg2). In others, the similarities occurred with the other covers, for the biomass of roots larger than 2 mm (BioRLg2), average diameter, partition of the length of roots smaller than 2 mm (PartLengRSm2), specific root length (SRL) and partition of the sectional area of roots smaller than 2 mm in relation to the total (PartSARSm2). In the 20-40 cm layer, NV showed the same behavior observed in the surface layer, i.e., higher values for BioRSm2, LengRSm2, LengRLg2, TotalRL, PartLengRSm2, SARSm2, TotalSA and VRSm2. For the other morphological parameters, in general, no significant differences were observed between forest covers.

Regarding the differences between depths, there was a reduction in the parameters only for NV and Nat, specifically BioRSm2, average diameter, LengRSm2, LengRLg2, TotalRL, SARSm2 and TotalSA. SRL showed the opposite, that is, its increase was observed in the second soil layer, for these same forest covers. The other study situations did not show significant differences.

Insert Table 3

The correlations between the variables determined for roots of the forest covers and C and N of soil organic matter fractions showed significant ($p<0.1$, t-test) and positive coefficients in the vast majority (Table 4). On the other hand, the non-significance and even the low values of the coefficients were observed when C and N of the organic matter fractions were correlated with trunk biomass and litter.

Insert Table 4

4. DISCUSSION

Although the fertilization, either mineral or organic, promotes increments in C and N stocks, one of the strategies for soil quality management and conservation (Leite et al., 2003; Loss et al., 2009, 2011; Valadão et al., 2011), there was no influence of the applied types on the organic attributes studied. Certainly, the fertilization applied at planting had effects on the growth of the forest species planted, that is, it provided better conditions for tree development, which could not be observed after 56 months.

However, the forest covers planted caused cumulative effects on the soil layers in the bauxite-mining area under rehabilitation, because the TOC stocks were higher compared to the area without cover (WCov), despite being smaller than the values in NV, the unmined reference area. Such increase in C stocks promoted by forest species (compared to the area without cover) is important at the beginning of the rehabilitation process, because SOM, under these conditions, is involved in the improvement of soil aggregation through the supply of organic residues that the management alternatives are able to introduce (Hosseini et al., 2015), and greater soil protection is expected to occur with the establishment of plants and root growth (Borges et al., 2019). On the other hand, soil TN stocks under the different forest covers did not differ from those of the WCov area. These results suggest that the period from the planting of forest covers was not yet sufficient for soil rehabilitation in the mined areas, since the return of soil organic attributes to the original state, represented by the reference area, not mined, rarely occurs in a short period of time.

Some studies indicate long periods for the recovery of soil organic matter, as are the cases of 18 years in a bauxite-mined area in Poços de Caldas, Minas Gerais (Carneiro et al., 2008) and 33 years in bauxite mining soils in Australia (Schwenke, Mulligan & Bell, 2000, 2000a, 2000b). The efficiency of the applied management techniques can reduce these periods, as noted by Anderson, Ingram & Stahl (2008), in a coal mining area, where 10 years were sufficient to recover the TOC stocks of the various studied areas, which were comparable to those unmined areas. One third of these areas cited by the researchers above showed higher TOC stocks than the reference areas.

Reduction of TOC stocks is caused not only by the removal of the surface soil layer and storage during the mining period (Carneiro et al., 2008), but also by the mixture of surface and subsurface horizons that are poorer in organic matter (Schwenke, Mulligan & Bell, 2000) or even sterile tailings eventually returned to the area to make the terrain uniform. In addition, soil turning and, consequently, the breakage of stable aggregates, exposes SOM that had been previously protected to accelerated microbiological decomposition (Chaplot & Cooper, 2015; Schimidt et al., 2011), favoring the losses of C through CO_2 emission. Studies carried out in bauxite mining soils in Minas Gerais showed a reduction of up to 99% in the contents of organic C and total N and microbial biomass (Carneiro et al., 2008). Reduction in the total stocks of TOC and TN were observed in the present study, and these stocks increased after planting the forest covers. Borges et al. (2019), when evaluating management practices to rehabilitate bauxite-mined areas, found that 19 months after application of the treatments, soil quality improved significantly in the plots under intercropping (grasses and leguminous crops) and fertilization with poultry litter (alone or in combination with chemical fertilizer), and these areas showed a higher soil quality index (˜ 23%) compared to post-mining soils. Therefore, the use of fertilization combined with the establishment of plant species in the area seems to be the most viable way for recovering the soil after bauxite mining.

Labile carbon (LC) is the one potentially more accessible to soil microorganisms and its determination has been recommended as an indicator of early changes in SOM, resulting from changes in land use, since it decreases and also recovers rapidly compared to TOC (BLAIR; LEFROY; LISLE, 1995). Although the three forest covers planted after bauxite mining tended to increase LC stocks in comparison to the area without cover (WCov), only Euc showed significant differences in the first soil layer. Considering the sum of all evaluated layers (0-60 cm), the influence of forest covers on soil LC was identified, increasing its stocks in comparison to the WCov area.

Rhizodeposition substantially contributes to supplying LC to the soil (Rasse; Rumpel & Dignac, 2005), as well as the supply of organic residues from the aerial part through the forest covers. Along 30 months of litterfall evaluation, Euc, Ap and Nat supplied about 20,810.0 kg ha^{-1}, 9,875 kg ha^{-1} and 15,805.16 kg ha^{-1} of aerial part organic residues, respectively, and the presence of this litter led to increased LC (1.55 t ha^{-1}) compared to its absence (1.33 t ha^{-1}). The forest covers enabled increments in LC stocks, in the 0-60 cm soil layer, in comparison to the WCov area on the order of 73%.

The carbon management index (CMI) is indicative of the impacts of land use on SOM stocks and can be used to monitor changes in C dynamics over time, considering a reference condition (Blair, Lefroy & Lisle, 1995), in this case, NV. Despite the lack of significant differences at each depth, the results indicated that the revegetated areas have a CMI below 100%, which suggest that the tested alternatives of cover have not yet recovered the stocks to the levels of the reference considered. However, when the 0-60 cm soil layer was evaluated, significant differences between the planted forest covers and the area without cover were observed. The CMI values of the mined area revegetated with Euc (50.58%), Ap (47.75%) and Nat (47.76%) demonstrate that the full recover C stocks has not yet been possible, since they are much lower than those in NV. However, the planting of these forest covers enabled, after 56 months, the increase of this index in comparison to the WCov area (24%), indicating the efficiency of these species for the recovery of C stocks of mined areas.

In the present study, the higher proportions of C and N associated with the MOM fraction were evident, which is due to the large specific surface of clay and silt, compared to sand (Zinn et al., 2007). Santos et al. (2011) observed, in an unimpacted area (native grassland), higher contents of C associated with minerals and attributed this effect to the mechanisms of chemical protection of organic matter by clay. Soils with low clay contents have lower protection of organic matter and low capacity of the mineral fraction to maintain high C stocks in MOM, imposing a certain condition of vulnerability to the management system employed (Santos et al., 2013).

Changes in TOC resulting from changes in land use occur mainly in the POM fraction, considered to be of faster response (Figueiredo, Resck & Carneiro, 2010; Lehmann, Cravo & Zech, 2001), so it is a sensitive indicator of changes in SOM. In this study, no changes were detected in the C and N stocks of POM in the soil of the forest covers used. There were only differences between NV, reference of unmined area, and the other covers. The lower stocks of C and N in the POM fraction of the mined areas are expected because of the impact caused by mining activities on soil organic attributes, such as the breakage of the physical protection of organic matter by soil aggregates and the exposure of this C to microbiological degradation (Lehmann, Cravo & Zech, 2001).

Bauxite mining resulted in a reduction of more than 90% in MBC stocks when the WCov area is compared to NV. The forest covers Euc, Ap and Nat increased this stock by about 62% compared to the WCov area, but it represents ˜24% of the MBC of NV. The rapid recovery of MBC is associated with revegetation of the area, which reestablishes C supply by the rhizosphere and provides organic C for the soil microbiota (Carneiro et al., 2008). The higher MBC/TOC ratio in NV may be related to the greater diversity of the organic substrate produced and supplied to the soil of these areas, besides the fact that there was no soil turning. The absence of differences in MBN stocks in the WCov, Euc, Ap and Nat areas, differing only from NV, with the best stocks, contradicts results reported under similar conditions (Carneiro et al., 2008), with recovery of MBN after one year of rehabilitation.

The correlations indicated that the C and N of the organic matter fractions are closely associated with the roots of plants of the various covers evaluated, especially in relation to the variables associated with fine roots. The participation of roots is reinforced when considering the relationships between the aerial part variables, either trunk biomass or litter, which showed non-significant correlation coefficients, expressed by the non-significance of the sources of variation in the ANOVA when the presence or absence of litter in a specific treatment was evaluated (Table S4).

The biomass of fine roots significantly contributes to C cycle in forest ecosystems (Finér et al., 2011). There are several mechanisms that can justify the greater association of roots with the highest stocks of C and N in the soil, including recalcitrance to the decomposition of the root material in relation to the aerial part of the plant, physicochemical protection by the interaction with soil minerals and occlusion in soil aggregates, which hampers its microbiological degradation (Rasse, Rampel & Dignac, 2005; Poirier, Roumet & Munson, 2019).

The results presented in this study confirm that soil quality indicators, such as total stocks of organic C, labile C and microbial biomass C, are sensitive in evaluating the dynamics of soil rehabilitation after bauxite mining activity. Despite the promising short-term effects of the use of forest species, combined with management practices such as fertilization, in the restoration of soil quality after bauxite mining evidenced in this study, the progress of these effects in the long term should be reevaluated in future studies.

5. CONCLUSIONS

The period from the planting of the forest covers was not sufficient to detect significant increases in TOC and TN stocks of mined areas to the same levels as those of NV, indicating the need for a longer period for rehabilitation.

The soil under eucalyptus and *A. peregrina* plantation showed higher C stocks in comparison to the mined area without cover.

Labile carbon and microbial biomass carbon are the organic attributes most sensitive to changes in soil under practices of rehabilitation from mining activity.

Roots are more associated with higher stocks of C and N than the aerial part of the trees (litter and trunk biomass).

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Table 1 . Stocks (t ha^{-1}) of total organic C and total N (TOC and TN), C/N ratio, labile C (LC) and C management index (CMI) of bauxite-mined soil under forest covers of eucalyptus (Euc), *A . peregrina* (Ap), mixed planting of native species (Nat) and two reference areas: without cover (WCov) and natural vegetation (NV), after 56 months of planting in the soil layers of 0-10, 10-20, 20-40, 40-60 and 0-60 cm

Depths (cm)	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers
	WCov	Euc	Ap	Nat	NV
	TOC (t ha^{-1})	TOC (t ha^{-1})	TOC (t ha^{-1})	TOC (t ha^{-1})	TOC (t ha^{-1})
0-10	13.92 Bc	21.54 Bb	21.26 Bb	19.98 Bb	54.59 Aa
10-20	12.06 Bbc	19.63 Bb	18.15 Bb	17.40 Bb	34.06 Ab
20-40	23.54 Ba	31.21 Ba	26.40 Ba	26.77 Ba	60.87 Aa
40-60	21.11 BCab	22.92 Bb	19.63 BCb	16.65 Bb	41.89 Ab
0-60	70.64 C	95.30 B	85.43 B	80.80 BC	191.42 A
	TN (t ha^{-1})	TN (t ha^{-1})	TN (t ha^{-1})	TN (t ha^{-1})	TN (t ha^{-1})
0-10	1.01 Bab	1.58 Bb	1.52 Bab	1.43 Bb	4.34 Aa
10-20	0.82 Bb	1.32 Bb	1.26 Bb	1.21 Bbc	2.82 Ab
20-40	1.55 Ba	2.04 Ba	1.72 Ba	1.81 Ba	4.59 Aa
40-60	1.17 Bab	1.39 Bb	1.26 Bb	0.95 Bc	3.023 Ab
0-60	4.57 B	6.34 B	5.75 B	5.40 B	14.78 A
	C/N	C/N	C/N	C/N	C/N
0-10	13.74 Ab	13.88 Ab	14.26 Ab	14.06 Ab	12.58 Aa
10-20	15.07 Aab	15.02 Aab	14.58 Ab	14.51 Ab	12.05 Aa
20-40	15.65 Aab	15.36 Aab	16.06 Aab	14.98 Ab	13.26 Aa
40-60	18.05 Aba	16.92 Ba	16.61 Ba	19.58 Aa	13.96 Ba
0-60	15.63 A	15.13 AB	15.15 AB	15.10 AB	12.96 B
	LC (t ha^{-1})	LC (t ha^{-1})	LC (t ha^{-1})	LC (t ha^{-1})	LC (t ha^{-1})
0-10	1.03 Ca	1.88 Ba	1.82 BCa	1.76 BCa	4.38 Aa

Depths (cm)	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers
10-20	0.61Ba	1.33 Bb	1.38 Bbc	1.35 Bb	2.50 Ac
20-40	1.03 Ba	2.03 Ba	1.78 Bab	1.63 Bab	3.58 Aa
40-60	0.86 Ba	1.12 Bb	1.07 Bc	1.21 Bb	2.24 Ac
0-60	3.53 C	6.35 B	6.04 B	5.96 B	12.70 A
	CMI (%)	CMI (%)	CMI (%)	CMI (%)	CMI (%)
0-10	25.5 Aa	44.09 Aa	41.66 Aa	40.56 Aa	100
10-20	29.36 Aa	53.09 Aa	55.55 Aa	54.61 Aa	100
20-40	33.54 Aa	58.78 Aa	51.27 Aa	48.27 Aa	100
40-60	31.34 Aa	49.63 Aa	48.63 Aa	55.14 Aa	100
0-60	27.57 B	50.58 A	47.75 A	47.76 A	100

Means followed by uppercase letters in the row compare the forest covers and by lowercase letters in the column compare each forest cover at the different depths; when followed by the same letter in the row or column, the means do not differ by Tukey test at 10% probability level.

Table 2 . Organic C and N stocks (t ha^{-1}) in mineral-associated (MOM) and particulate (POM) organic matter fractions and in microbial biomass (MB) in bauxite-mined area with soil rehabilitation under forest covers of eucalyptus (Euc), *A. Peregrina* (Ap), mixed planting of native species (Nat) and two reference areas: without cover (WCov) and NV, after 56 months of planting in the soil layers of 0-10, 10-20, 20-40 and 40-60 cm

Depths (cm)	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers
	WCov	Euc	Ap	Nat	NV
	CMOM (t ha-1)	CMOM (t ha-1)	CMOM (t ha-1)	CMOM (t ha-1)	CMOM (t ha-1)
0-10	12.59 Ba	17.46 Bb	18.46 Bb	17.43 Bb	41.88 Ab
10-20	11.47 Ba	17.42 Bb	16.63 Bb	15.88 Bb	29.45 Ac
20-40	19.67 Ca	27.81 Ba	22.75 BCa	24.41 Ba	57.03 Aa
40-60	17.92 BCa	21.02 Bb	17.45 BCb	14.42 Cb	36.93 Abc
0-60	61.65 B	83.71 B	75.29 B	72.14 B	165.29 A
	CPOM (t ha-1)	CPOM (t ha-1)	CPOM (t ha-1)	CPOM (t ha-1)	CPOM (t ha-1)
0-10	1.33 Ba	4.07 Ba	2.79 Bab	2.55 Ba	12.71 Aa
10-20	0.59 Ba	2.21 Bb	1.52 Bb	1.52 Ba	4.61 Ab
20-40	3.87 Aa	3.39 Aab	3.63 Aa	2.36 Aa	3.84 Ab
40-60	3.19 Aa	1.89 Ab	2.18 Aab	2.24 Aa	4.96 Ab
0-60	8.98 B	11.57 B	10.13 B	8.67 B	26.12 A
	NMOM (t ha-1)	NMOM (t ha-1)	NMOM (t ha-1)	NMOM (t ha-1)	NMOM (t ha-1)
0-10	0.87 Ba	1.39 Bab	1.37 Bab	1.26 Bab	3.33 Aab
10-20	0.65 Ba	1.24 Bb	1.11 Bb	1.06 Bb	2.27 Ab
20-40	1.34 Ba	1.70 Ba	1.54 Ba	1.62 Bb	4.05 Aa
40-60	1.07 Ba	1.23 Bb	1.11 Bb	0.91 Bb	2.66 Abc
0-60	3.94 B	5.57 B	5.14B	4.85 B	12.32 A
	NPOM (t ha-1)	NPOM (t ha-1)	NPOM (t ha-1)	NPOM (t ha-1)	NPOM (t ha-1)
0-10	0.14 Ba	0.19 Bab	0.15 Ba	0.17 Ba	1.01 Aa
10-20	0.17 Aa	0.08 Ac	0.15 Aa	0.15 Aa	0.55 Ab
20-40	0.21 Aa	0.34 Aa	0.17 Aa	0.19 Aa	0.54 Ab

Depths (cm)	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers
40-60	0.13 Aa	0.16 Aab	0.15 Aa	0.04 Ba	0.36 Ab
0-60	0.65 B	0.77 B	0.62 B	0.54 B	2.45 A
MBC (t ha-1)	MBC (t ha-1)	MBC (t ha-1)	MBC (t ha-1)	MBC (t ha-1)	MBC (t ha-1)
0-10	0.0602 C	0.1781 B	0.1595 B	0.1506 B	0.6839 A
MBN (t ha-1)	MBN (t ha-1)	MBN (t ha-1)	MBN (t ha-1)	MBN (t ha-1)	MBN (t ha-1)
0-10	0.0177 B	0.0241 B	0.0275 B	0.0214 B	0.0660 A

CMOM= C from mineral-associated organic matter; CPOM= C from particulate organic matter; NMOM = N from mineral-associated organic matter; NPOM = N from particulate organic matter; MBC = carbon from soil microbial biomass; MBN = nitrogen from soil microbial biomass. Means followed by uppercase letters in the row compare the forest covers and by lowercase letters in the column compare each forest cover at the different depths; when followed by the same letter in the row or column, the means do not differ by Tukey test at 10% probability level.

Table 3 . Root biomass and root morphological attributes in bauxite-mined area with soil rehabilitation under forest covers of eucalyptus (Euc), *A. peregrina* (Ap), mixed planting of native species (Nat) and NV, after 56 months of planting, in the soil layers of 0-20 and 20-40 cm

Depths (cm)	Depths (cm)	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Fore cove
		Euc BioRSm2 (t ha-1)	Euc BioRSm2 (t ha-1)	Euc BioRSm2 (t ha-1)	Euc BioRSm2 (t ha-1)	Euc BioRSm2 (t ha-1)	Euc BioRSm2 (t ha-1)	Ap BioRSm2 (t ha-1)	Ap BioRSm2 (t ha-1)	Ap BioRSm2 (t ha-1)	Ap BioRSm2 (t ha-1)	Ap BioRSm2 (t ha-1)	Ap BioRSm2 (t ha-1)	Ap BioRSm2 (t ha-1)	Nat BioRSm2 (t ha-1)	Nat BioRSm2 (t ha-1)	Nat BioR (t ha-1)
0-20	0-20	0-20	0.53 Ca	0.53 Ca	0.53 Ca	0.53 Ca	0.53 Ca	0.53 Ca	0.53 Ca	0.87 BCa	0.87 BCa	0.87 BCa	0.87 BCa	0.87 BCa	0.87 BCa	0.87 BCa	1.88 Ba
20-40	20-40	20-40	0.33 Ba	0.33 Ba	0.33 Ba	0.33 Ba	0.33 Ba	0.33 Ba	0.33 Ba	0.52 Ba	0.52 Ba	0.52 Ba	0.52 Ba	0.52 Ba	0.52 Ba	0.52 Ba	0.51 Bb
		BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioRLg2 (t ha-1)	BioR (t ha-1)
0-20	0-20	0.89 Aa	0.89 Aa	0.89 Aa	0.89 Aa	0.89 Aa	0.89 Aa	0.22 Aa	0.22 Aa	0.22 Aa	0.22 Aa	0.22 Aa	0.22 Aa	0.22 Aa	1.98 Aa	1.98 Aa	1.98 Aa
20-40	20-40	0.99 Aa	0.99 Aa	0.99 Aa	0.99 Aa	0.99 Aa	0.99 Aa	0.11 Aa	0.11 Aa	0.11 Aa	0.11 Aa	0.11 Aa	0.11 Aa	0.11 Aa	1.23 Aa	1.23 Aa	1.23 Aa
		TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	TotalRB (t ha-1)	Tota (t ha-1)
0-20	0-20	1.42 Ba	1.42 Ba	1.42 Ba	1.42 Ba	1.42 Ba	1.42 Ba	1.10 Ba	1.10 Ba	1.10 Ba	1.10 Ba	1.10 Ba	1.10 Ba	1.10 Ba	3.86 ABa	3.86 ABa	3.86 ABa
20-40	20-40	1.32 Aa	1.32 Aa	1.32 Aa	1.32 Aa	1.32 Aa	1.32 Aa	0.62 Aa	0.62 Aa	0.62 Aa	0.62 Aa	0.62 Aa	0.62 Aa	0.62 Aa	1.74 Aa	1.74 Aa	1.74 Aa
		PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)	PartBioRSm2 (%)
0-20	0-20	43.30 Ba	43.30 Ba	43.30 Ba	43.30 Ba	43.30 Ba	43.30 Ba	43.30 Ba	82.99 Aa	82.99 Aa	82.99 Aa	82.99 Aa	82.99 Aa	82.99 Aa	82.99 Aa	50.39 ABa	50.3 ABa

Depths (cm)	Depths (cm)	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers
20-40	20-40	31.08 Ba	31.08 Ba	31.08 Ba	31.08 Ba	31.08 Ba	31.08 Ba	31.08 Ba	83.24 Aa	83.24 Aa	83.24 Aa	83.24 Aa	83.24 Aa	83.24 Aa	83.24 Aa	35.57 Ba	35.57 Ba
		Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)	Average diameter (mm)
0-20	0-20	1.24 ABa	1.24 ABa	1.24 ABa	1.24 ABa	1.24 ABa	0.95 Ba	0.95 Ba	0.95 Ba	0.95 Ba	0.95 Ba	0.95 Ba	0.95 Ba	1.64 ABa	1.64 ABa	1.64 ABa	1.64 ABa
20-40	20-40	1.50 Aa	1.50 Aa	1.50 Aa	1.50 Aa	1.50 Aa	1.30 Aa	1.30 Aa	1.30 Aa	1.30 Aa	1.30 Aa	1.30 Aa	1.30 Aa	1.53 Aa	1.53 Aa	1.53 Aa	1.53 Aa
		LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)	LengRSm2 (m)
0-20	0-20	1.01E+07 Ba	1.01E+07 Ba	1.01E+07 Ba	1.01E+07 Ba	1.01E+07 Ba	1.01E+07 Ba	8.87E+06 Ba	8.87E+06 Ba	8.87E+06 Ba	8.87E+06 Ba	8.87E+06 Ba	8.87E+06 Ba	8.87E+06 Ba	1.09E+07 Ba	1.09E+07 Ba	1.09E+07 Ba
20-40	20-40	6.13E+06 Ba	6.13E+06 Ba	6.13E+06 Ba	6.13E+06 Ba	6.13E+06 Ba	6.13E+06 Ba	4.82E+06 Ba	4.82E+06 Ba	4.82E+06 Ba	4.82E+06 Ba	4.82E+06 Ba	4.82E+06 Ba	4.82E+06 Ba	6.83E+06 Bb	6.83E+06 Bb	6.83E+06 Bb
		LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)	LengRLg2 (m)
0-20	0-20	3.53E+05 Ba	3.53E+05 Ba	3.53E+05 Ba	3.53E+05 Ba	3.53E+05 Ba	3.53E+05 Ba	1.79E+05 Ba	1.79E+05 Ba	1.79E+05 Ba	1.79E+05 Ba	1.79E+05 Ba	1.79E+05 Ba	1.79E+05 Ba	1.05E+06 Aa	1.05E+06 Aa	1.05E+06 Aa
20-40	20-40	3.03E+05 Ba	3.03E+05 Ba	3.03E+05 Ba	3.03E+05 Ba	3.03E+05 Ba	3.03E+05 Ba	3.56E+05 Ba	3.56E+05 Ba	3.56E+05 Ba	3.56E+05 Ba	3.56E+05 Ba	3.56E+05 Ba	3.56E+05 Ba	3.22E+05 Bb	3.22E+05 Bb	3.22E+05 Bb
		TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)	TotalRL (m)
0-20	1.05E+07 Ba	1.05E+07 Ba	1.05E+07 Ba	9.04E+06 Ba	9.04E+06 Ba	9.04E+06 Ba	9.04E+06 Ba	9.04E+06 Ba	9.04E+06 Ba	9.04E+06 Ba	2.09E+07 Ba	2.09E+07 Ba	2.09E+07 Ba	2.09E+07 Ba	2.09E+07 Ba	2.09E+07 Ba	2.09E+07 Ba
20-40	6.43E+06 Ba	6.43E+06 Ba	6.43E+06 Ba	5.18E+06 Ba	5.18E+06 Ba	5.18E+06 Ba	5.18E+06 Ba	5.18E+06 Ba	5.18E+06 Ba	5.18E+06 Ba	7.15E+06 Ba	7.15E+06 Ba	7.15E+06 Ba	7.15E+06 Ba	7.15E+06 Ba	7.15E+06 Ba	7.15E+06 Ba
		PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)	PartLengRSm2 (%)
0-20	96.57 ABa	96.57 ABa	96.57 ABa	96.57 ABa	98.02Aa	98.02Aa	98.02Aa	98.02Aa	98.02Aa	98.02Aa	98.02Aa	94.58 Ba	94.58 Ba	94.58 Ba	94.58 Ba	94.58 Ba	94.58 Ba
20-40	94.89 Bb	94.89 Bb	94.89 Bb	94.89 Bb	93.40 Bb	93.40 Bb	93.40 Bb	93.40 Bb	93.40 Bb	93.40 Bb	93.40 Bb	95.01 Ba	95.01 Ba	95.01 Ba	95.01 Ba	95.01 Ba	95.01 Ba
		SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)	SRL (m t-1)
0-20	0-20	1.88E+07 Aa	1.88E+07 Aa	1.88E+07 Aa	1.88E+07 Aa	1.88E+07 Aa	1.88E+07 Aa	1.07E+07 Ba	1.07E+07 Ba	1.07E+07 Ba	1.07E+07 Ba	1.07E+07 Ba	1.07E+07 Ba	1.07E+07 Ba	1.04E+07 Bb	1.04E+07 Bb	1.04E+07 Bb
20-40	20-40	1.85E+07 Aa	1.85E+07 Aa	1.85E+07 Aa	1.85E+07 Aa	1.85E+07 Aa	1.85E+07 Aa	9.47E+06 Ba	9.47E+06 Ba	9.47E+06 Ba	9.47E+06 Ba	9.47E+06 Ba	9.47E+06 Ba	9.47E+06 Ba	1.33E+07 ABa	1.33E+07 ABa	1.33E+07 ABa
		SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)	SARSm2 (m2 ha-1)

Depths (cm)	Depths (cm)	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers	Forest covers
0-20	0-20	1.13E+04 Ca	1.43E+04 Ca	1.43E+04 Ca	1.43E+04 Ca	1.43E+04 Ca	1.43E+04 Ca	1.40E+04 Ca	1.40E+04 Ca	1.40E+04 Ca	1.40E+04 Ca	1.40E+04 Ca	1.40E+04 Ca	1.40E+04 Ca	3.51E+04 Ba	3.51E+04 Ba	3.51 Ba
20-40	20-40	7.00E+03 Ba	7.30E+03 Ba	7.30E+03 Ba	7.30E+03 Ba	7.30E+03 Ba	7.30E+03 Ba	7.93E+03 Ba	7.93E+03 Ba	7.93E+03 Ba	7.93E+03 Ba	7.93E+03 Ba	7.93E+03 Ba	7.93E+03 Ba	1.10E+04 Ba	1.40E+04 Ba	1.40 Ba
		SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SARLg2 (m2 ha-1)	SAR (m2 ha-1)
0-20	0-20	4.42E+03 Ba	4.42E+03 Ba	4.42E+03 Ba	4.42E+03 Ba	4.42E+03 Ba	4.42E+03 Ba	1.90E+03 Ba	1.90E+03 Ba	1.90E+03 Ba	1.90E+03 Ba	1.90E+03 Ba	1.90E+03 Ba	1.90E+03 Ba	1.18E+04 ABa	1.18E+04 ABa	1.18 ABa
20-40	20-40	4.53E+03 Aa	4.53E+03 Aa	4.53E+03 Aa	4.53E+03 Aa	4.53E+03 Aa	4.53E+03 Aa	4.27E+03 Aa	4.27E+03 Aa	4.27E+03 Aa	4.27E+03 Aa	4.27E+03 Aa	4.27E+03 Aa	4.27E+03 Aa	3.96E+04 Aa	3.96E+04 Aa	3.96 Aa
		TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	TotalSA (m2 ha-1)	Tota (m2 ha-1)
0-20	1.57E+04 Ca	1.57E+04 Ca	1.57E+04 Ca	1.57E+04 Ca	1.57E+04 Ca	1.29E+04 Ca	1.29E+04 Ca	1.29E+04 Ca	1.29E+04 Ca	1.29E+04 Ca	1.29E+04 Ca	1.29E+04 Ca	4.60E+04 Ba	4.60E+04 Ba	4.60E+04 Ba	4.60E+04 Ba	4.60 Ba
20-40	1.15E+04 Ba	1.45E+04 Ba	1.45E+04 Ba	1.45E+04 Ba	1.45E+04 Ba	1.22E+04 Ba	1.22E+04 Ba	1.22E+04 Ba	1.22E+04 Ba	1.22E+04 Ba	1.22E+04 Ba	1.22E+04 Ba	1.5E+04 Bb	1.5E+04 Bb	1.5E+04 Bb	1.5E+04 Bb	1.5E Bb
		PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)	PartSARSm2 (%)
0-20	71.22 Aa	71.22 Aa	71.22 Aa	71.22 Aa	85.38 Aa	85.38 Aa	85.38 Aa	85.38 Aa	85.38 Aa	85.38 Aa	85.38 Aa	74.40 Aa	74.40 Aa	74.40 Aa	74.40 Aa	74.40 Aa	74.4 Aa
20-40	60.45 Ba	60.45 Ba	60.45 Ba	60.45 Ba	67.07 ABb	67.07 ABb	67.07 ABb	67.07 ABb	67.07 ABb	67.07 ABb	67.07 ABb	73.82 ABa	73.82 ABa	73.82 ABa	73.82 ABa	73.82 ABa	73.8 ABa
		VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRSm2 (m3 ha-1)	VRS (m3 ha-1)
0-20	0-20	1.63 Ba	1.63 Ba	1.63 Ba	1.63 Ba	1.63 Ba	1.63 Ba	2.52 Ba	2.52 Ba	2.52 Ba	2.52 Ba	2.52 Ba	2.52 Ba	2.52 Ba	8.39 Aa	8.39 Aa	8.39 Aa
20-40	20-40	1.03 Ba	1.03 Ba	1.03 Ba	1.03 Ba	1.03 Ba	1.03 Ba	1.33 Ba	1.33 Ba	1.33 Ba	1.33 Ba	1.33 Ba	1.33 Ba	1.33 Ba	2.06 Bb	2.06 Bb	2.06 Bb
		VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRLg2 (m3 ha-1)	VRL (m3 ha-1)
0-20	0-20	2.35 Ba	2.35 Ba	2.35 Ba	2.35 Ba	2.35 Ba	2.35 Ba	0.61 Ba	0.61 Ba	0.61 Ba	0.61 Ba	0.61 Ba	0.61 Ba	0.61 Ba	5.05 ABa	5.05 ABa	5.05 ABa
20-40	20-40	2.67 Aa	2.67 Aa	2.67 Aa	2.67 Aa	2.67 Aa	2.67 Aa	4.29 Aa	4.29 Aa	4.29 Aa	4.29 Aa	4.29 Aa	4.29 Aa	4.29 Aa	2.31 Ab	2.31 Ab	2.31 Ab

BioRSm2, BioRLg2 and TotalRB: biomass of roots smaller and larger than 2 mm and total root biomass, respectively; LengRSm2, LengRLg2 and TotalRL: length of roots smaller and larger than 2 mm and total root length, respectively; PartLengRSm2: partition of the length of smaller roots in relation to the total length; SRL: specific root length; SARSm2 and SARLg2: sectional area of roots smaller and larger than 2 mm, respectively; PartSARSm2: partition of the sectional area of the smaller roots in relation to the total;

VRSm2 and VRLg2: volume of roots smaller and larger than 2 mm. Means followed by uppercase letters in the row compare the forest covers and by lowercase letters in the column compare each forest cover at the different depths; when followed by the same letter in the row or column, the means do not differ by Tukey test at 10% probability level.

Table 4. Pearson's correlation coefficients between soil organic attributes and root biomass and root morphological attributes in bauxite-mined area with soil rehabilitation under forest covers of eucalyptus (Euc), *A. peregrina* (Ap), mixed planting of native species (Nat) and natural vegetation (NV), after 56 months of planting in the soil layers of 0-20 and 20-40 cm

Variables	TOC	LC	CMOM	CPOM	TN	NMOM	NPOM
	dag kg^{-1}	dag kg^{-1}	dag kg^{-1}	dag kg^{-1}	dag kg^{-1}	dag kg^{-1}	dag kg^{-1}
BioRSm2 (g)	0.84^*	0.85^*	0.81^*	0.78^*	0.86^*	0.89^*	0.82^*
BioRLg2 (g)	0.91^*	0.81^*	0.90^*	0.75^*	0.91^*	0.90^*	0.83^*
TotalRB (g)	0.90^*	0.83^*	0.89^*	0.77^*	0.91^*	0.92^*	0.84^*
PartBioRSm2 (%)	-0.30^{ns}	-0.23^{ns}	-0.36^{ns}	-0.02^{ns}	-0.26^{ns}	-0.21^{ns}	-0.31^{ns}
Average diameter (mm)	0.20^{ns}	0.36^{ns}	0.21^{ns}	0.13^{ns}	0.20^{ns}	0.10^{ns}	0.40^{ns}
LengRSm2 (cm)	0.90^*	0.82^*	0.88^*	0.76^*	0.91^*	0.93^*	0.81^*
LengRLg2 (cm)	0.69^*	0.69^*	0.67^*	0.62^*	0.70^*	0.77^*	0.67^*
TotalRL (cm)	0.90^*	0.82^*	0.88^*	0.76^*	0.90^*	0.93^*	0.80^*
PartLengRSm2 (%)	0.00^{ns}	-0.16^{ns}	-0.01^{ns}	0.05^{ns}	0.01^{ns}	0.11^{ns}	-0.19^{ns}
SRL (cm/g)	0.28^{ns}	0.03^{ns}	0.30^{ns}	0.16^{ns}	0.27^{ns}	0.30^{ns}	0.04^{ns}
SARSm2 (cm^2)	0.81^*	0.78^*	0.79^*	0.71^*	0.82^*	0.88^*	0.75^*
SARLg2 (cm^2)	0.77^*	0.74^*	0.74^*	0.68^*	0.78^*	0.83^*	0.73^*
PartSARSm2 (%)	0.08^{ns}	-0.06^{ns}	0.06^{ns}	0.14^{ns}	0.09^{ns}	0.21^{ns}	-0.12^{ns}
VRSm2 (cm^3)	0.67^*	0.71^*	0.67^*	0.54^*	0.68^*	0.76^*	0.65^*
VRLg2 (cm^3)	0.75^*	0.72^*	0.71^*	0.75^*	0.77^*	0.75^*	0.77^*
Litter (kg)	0.05^{ns}	0.14^{ns}	0.07^{ns}	-0.01^{ns}	0.03^{ns}	0.09^{ns}	-0.13^{ns}
Trunk biomass (kg)	0.08^{ns}	0.10^{ns}	0.08^{ns}	0.06^{ns}	0.06^{ns}	0.07^{ns}	-0.11^{ns}

BioRSm2, BioRLg2 and TotalRB: biomass of roots smaller and larger than 2 mm and total root biomass, respectively; PartBioRSm2: partition of the biomass of roots smaller than 2 mm in relation to the total; LengRSm2, LengRLg2 and TotalRL: length of roots smaller and larger than 2 mm and total root length, respectively; PartLengRSm2: partition of the length of smaller roots in relation to the total length; SRL: specific root length; SARSm2 and SARLg2: sectional area of roots smaller and larger than 2 mm, respectively; PartSARSm2: partition of the sectional area of the smaller roots in relation to the total; VRSm2 and VRLg2: volume of roots smaller and larger than 2 mm; TOC: total organic carbon; LC: labile carbon; CMOM= C from mineral-associated organic matter; CPOM= C from particulate organic matter; TN: total nitrogen; NMOM = N from mineral-associated organic matter; NPOM = N from particulate organic matter. *Significant at 10% probability level; not significant at 10% probability level