Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Soil quality indicators for monitoring the short-term effects of mined soil rehabilitation strategies for bauxite

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ABSTRACT: Mining is a significant driver of soil mobilization, which impacts its physical, chemical, and biological properties. Changes in land-use affect the distribution of organic matter fractions in stable aggregates, a process that is still poorly understood, especially in drastically altered areas. Recovering and monitoring soil quality to ensure the sustainable development of agricultural crops in these areas after mining is challenging. This study aimed to evaluate the influence of agronomic practices in soil rehabilitation in a bauxite-mined area after three years of field experiment installations through an assessment of organic properties in soil and aggregate classes; an attempt was also made at proposing and elaborating a Soil Quality Index (SQI), which encompasses the soil's physical, chemical, and organic properties. Different combinations of fertilization treatments and ground cover plants intercropping with coffee were evaluated as rehabilitation practices. The results showed that after three years of rehabilitation, when organic (OF), chemical (CF), and OF+CF fertilizers were applied to the areas of coffee intercropped with Brachiaria (B), they provided higher C and N contents to the soil and aggregates classes, as well as the compartments of soil organic matter (SOM). The minimum set of soil quality indicators for reclaimed bauxite-mined areas was composed of organic indicators: labile organic carbon (LOC) and mineral-associated organic matter (C-MOM); chemical indicators including pH and effective cation-exchange capacity (t), and physical indicators such as the bulk density (BD) and stable aggregates index in water (SAI_W). The t and pH were the variables most sensitive to the management systems implanted during the rehabilitation of the mined area, and, therefore, were considered the best indicators of soil quality. Brachiaria was the cover plant that contributed most to improving the soil quality of mined bauxite areas by increasing the SQI, especially when fertilized. In general, when applied to the Brachiaria, the OF+CF fertilization presented a SQI of 0.78, differing statistically from that of the natural vegetation (1.00). Fertilizers and cover crops in association with coffee in the bauxite-mined areas improved the physical, chemical, and organic properties of the soil, thus representing a viable option for reconditioning mineral exploration areas.

Keywords: soil quality indicators, physical fractionation, organic matter compartments, soil recovery.

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Received: September 26, 2022
Approved: November 29, 2022

How to cite: Cavalcante DM, Silva IR, Oliveira TS. Soil quality indicators for monitoring the short-term effects of mined soil rehabilitation strategies for bauxite. Rev Bras Cienc Solo. 2023;47:e0220126.
https://doi.org/10.36783/18069657rbcs20220126

Editors: José Miguel Reichert and João Tavares Filho.

INTRODUCTION

Mineral extraction represents an important activity contributing to the economic development of a country. Mining affects the sustainability of natural resources, especially that of soil and water. Studies about environmental impacts caused by mining activities are of increasing environmental relevance.

The Brazilian mineral industry has helped generate important surpluses in the country's trade balance, having exported more than 403 million tons of mineral goods in 2017. This generated foreign exchange on FOB (Free On Board) US$ 28,3 billion, representing 13 % of Brazil's total exports and 30.5 % of the trade balance (IBRAM, 2018). Tonietto and Silva (2011) reported that 67 % of the ore reserves measured and indicated in Brazil are located in the Minas Gerais State. According to statistics from the National Department of Mineral Production (NDMP), Minas Gerais is the Brazil's second largest producer of bauxite and, in 2016, produced the equivalent of R$ 112,199,137.00 (DNPM, 2018).

Soil degradation reduces agricultural production capacity resulting from its intensive use, causing changes in soil's physical, chemical, and biological properties. In addition to deforestation, the removal of topsoil exposes the remaining soil to erosive processes. Moreover, the withdrawal of consolidated material exposes the surrounding communities to dust and noise pollution. Therefore, mining activities in Brazil are positive for the municipalities, not only due to the taxes collected, but also through the direct and indirect jobs they generate. Rehabilitation efforts in mining areas have been conducted by companies, environmental organizations, universities, and research institutes that have been seeking effective procedures to reestablish the essential processes of the soil and affected ecosystems (Carneiro et al., 2008).

Rehabilitation involves the process of reversing the damage affecting degraded lands and turning the latter into productive and self-sustaining lands (Gripp and Nonato, 1993). The Federal Constitution of Brazil, Decree 97.632/89 - art. 3, establishes that the degraded areas must aim to return to a form of use to achieve stability of the environment, according to a pre-established plan for land-use. Rehabilitation practices that provide a higher contribution of soil organic matter (SOM) are more successful because it can improve soil properties. They are also important for maintaining the soil quality of the ecosystems (Santos et al., 2011; Pillon et al., 2011; Cavalcante et al., 2019).

One of the indicators of the highest importance in the evolution of soil quality is its organic matter content (Doran and Parkin, 1994; Canals et al., 2007). Organic matter helps to indicate the quality of the management system that should be adopted for the ecological recovery of degraded areas (Bao et al., 2017). The decrease of C and N contents, which are considered essential propertes to the proper functioning of soils, has been reported in papers regarding the evaluation of areas under rehabilitation after mining (Trindade et al., 2000; Carneiro et al., 2008; Lunardi Neto et al., 2008; Cavalcante et al., 2019). Studies conducted on bauxite mining soils in Minas Gerais have shown a reduction of 99 % of the total C and N contents, microbial biomass, and enzymatic activity of the soil (Carneiro et al., 2008).

Some strategies for the rehabilitation of mined areas have been used to increase the SOM through their revegetation by grasses and native plants (Vickers et al., 2012; Kneller et al., 2018; Iskandar et al., 2022), the use of leguminous plant species (Mukhopadhyay and Masto, 2016), that besides of C, improves N content in the soil (Roberts et al., 2015; Rodríguez-Vila et al., 2016). An increase or decrease in the SOM due to soil management practices implies benefits or damage to the system, respectively (Canals, 2007).

As a soil quality indicator (SQI), Reeves (1997) reported that the soil organic carbon (SOC) was a fundamental SQI in long-term studies. The SOC frequently does not present a high sensibility to the changes caused by determinate management systems in the short and medium terms; therefore, different SOM fractions can instead be used to verify the susceptibility of soils to the management types employed, according to the degree of lability that present (Gregorich et al., 1988; Pinheiro et al., 2004; Conceição et al., 2008, 2014). The study of soil organic compartments using SOM fractionation has provided a better understanding of nutrient releases and organic matter stabilization under changes in soil management and the environment (Lima et al., 2008; Alcântara Neto et al., 2011; Pessoa et al., 2012).

Different properties such as cation exchange capacity (CEC), soil biological activity, soil structure, pH, rainwater infiltration, soil erosion, salinization, etc., are all related to soil quality. However, the SOM compartments obtained by physical fractionation have not yet been used to evaluate soil quality, although these fractions are of great importance for the monitoring and evaluation of edaphic changes caused by the mining process.

Considering the reconditioning of the physical, chemical, and organic soil properties of mined areas, this study used organic and chemical fertilizers, as well as cover crops to: (*i*) determine the C and N contents in soil, soil organic fractions, and aggregate classes; (*ii*) elect the minimum number of indicators of soil quality encompassing physical, chemical, and organic properties; and (*iii*) use quality indicators to investigate the effects of different fertilization procedures and cover crops on coffee cultivation on the recovery of bauxite-mined areas.

MATERIALS AND METHODS

Study area and experimental details

The study was carried out in the bauxite-mined area located in the Minas Gerais Forest Zone, in the municipality of São Sebastião da Vargem Alegre, Minas Gerais, Brazil (W 42° 35′ 02.18″ and S 21° 01′ 58.98″) (Figure 1). The ore extraction concession belongs to the Brazilian Aluminum Company – Votorantim Metals (Companhia Brasileira de Alumínio – Votorantim Metais). The terrain of the region is strongly rolling and the soil is classified as *Latossolos Vermelho-Amarelos Distróficos típicos*, according to the Brazilian Soil Classification System (Santos et al., 2018), which corresponds to an Oxisols (Soil Survey Staff, 2014). The climate is defined as high-altitude tropical (Cwa) according to the Köppen-Geiger classification system (Köppen, 1936), with a mean annual temperature and rainfall of 23.5 °C and 1,564 mm, respectively.

After three years of experiment implementation (Figure 2), the rehabilitation of the mined area was first assessed by Cavalcante et al. (2019). A randomized block design (RBD) experiment with a split-plot arrangement was used with four replicates, in which the treatments consisted of coffee cultivation, different types of fertilization procedures, and different cover crops between the rows: no fertilization (NF); organic fertilization (OF); chemical fertilization (CF); organic + chemical fertilization (OF+CF); no plants (NP); stylosanthes (S); Brachiaria (B); and an area covered by a fragment of native vegetation (NV) was considered as reference area. The specifications of the treatments are described in table 1. Further details can be found in Cavalcante et al. (2019).

Soil sampling and physical analysis

All soil samples were collected from 0.00-0.20 m soil layer, and their physical, chemical, and organic properties were analyzed. Soil physical propertiess were determined following the methodology proposed by Donagemma et al. (2011). Bulk density (BD) was obtained with the volumetric ring method using undisturbed soil. All other soil analyses were determined on <2 mm soil fractions. Clay, silt, and coarse and fine sand were obtained

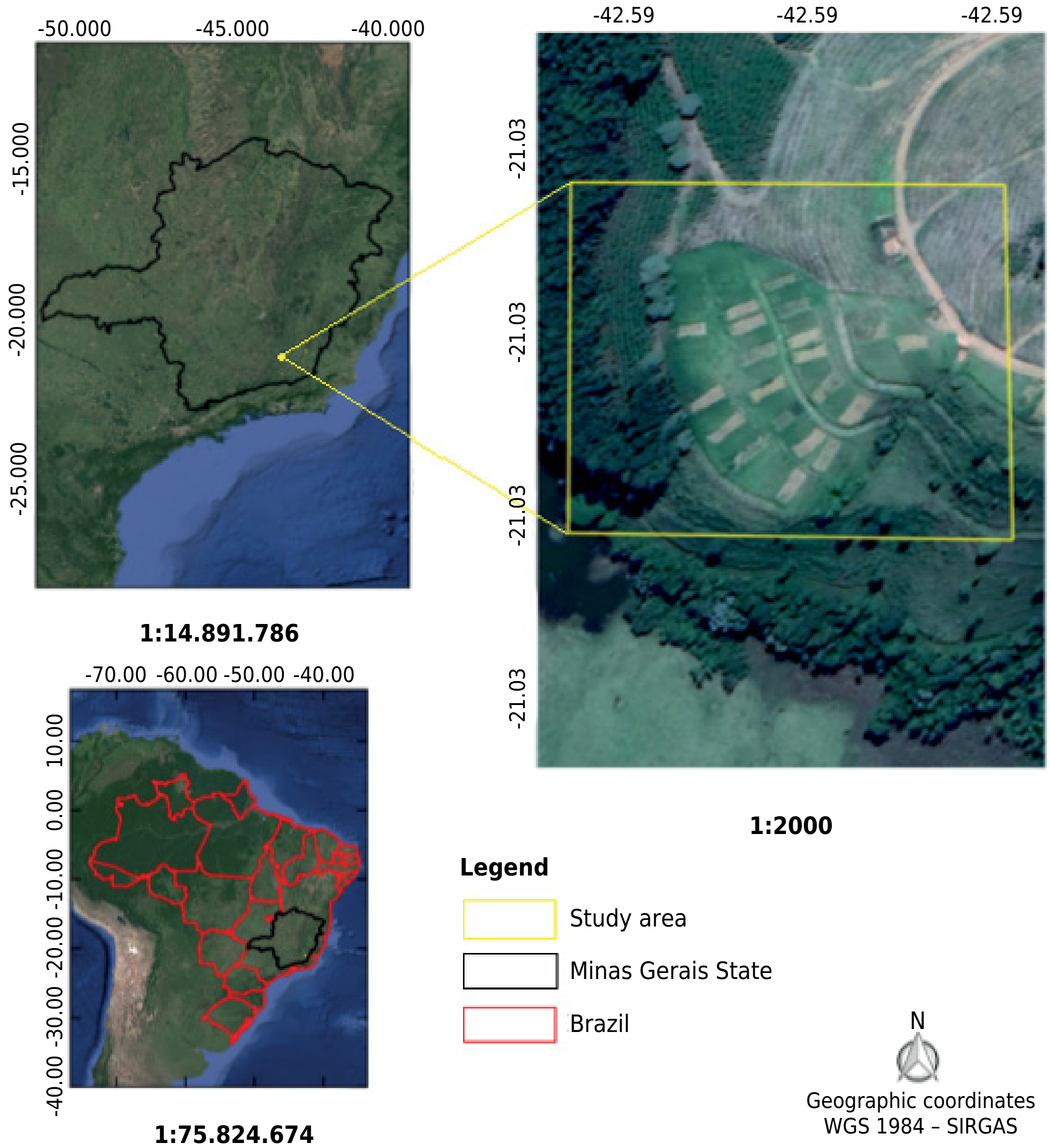

Figure 1. Location of the study area in the municipality of São Sebastião da Vargem Alegre, Minas Gerais, Brazil (Minas Forest Zone) (Cavalcante et al., 2019).

by physical dispersion with slow agitation for 16 hs (50 rpm) and chemical dispersion with NaOH 0.1 mol L^{-1}; the sand contents were determined by sieving and the amounts of clay and silt were quantified with the pipette method. The total porosity (TP) was determined by the following equation:

$$1 - \left(\frac{\rho_s}{BD}\right) \times 100 \qquad \text{Eq. 1}$$

in which: ρ_s is the particle density obtained by the volumetric balloon method; microporosity (Micro) was determined by weighing after equilibrium at -6 kPa in a tension table, and macroporosity (Macro) was defined as: TP - Micro.

Wet separation of aggregates was performed by a Yoder type vertical oscillating apparatus (26 cycles min^{-1} and 5.0 cm vertical amplitude for 15 min), resulting in six stable aggregate classes: 4.75 – 2.00; 2.00 – 1.00; 1.00 – 0.50; 0.50 – 0.25; 0.25 – 0.105; and <0.105 mm (Kemper and Chepil, 1965). The proportions of water-stable aggregates (WSA) were used to calculate the mean weight-diameter (MWD_W) and the geometric mean diameter (GMD_W) using the following expressions:

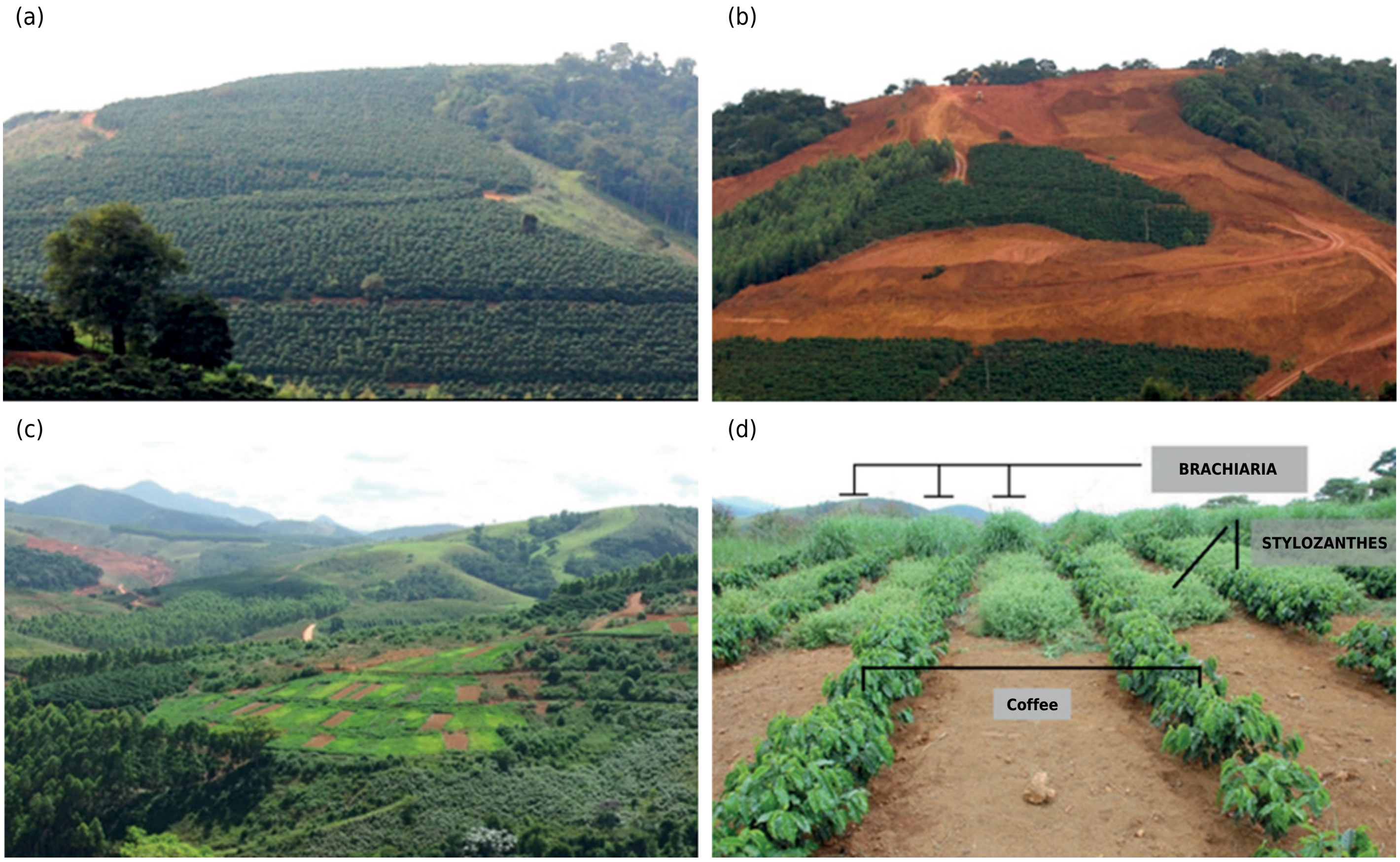

Figure 2. Area preliminarily cultivated with coffee (last ten years) (a); reconfiguration of the mined area and replacement of the A horizon soil stored prior to mining (b); experimental area comprising zones of coffee cultivation, different types of fertilization treatments, and intercropping cover crops species (c); and experimental layout with ground cover treatments implanted between the crop rows (d) (Cavalcante et al., 2019).

$$MWD_W = \sum_{i=1}^{n} (w_i\, x_i) \quad \text{Eq. 2}$$

$$GMD_W = 10 \sum_{i=1}^{n} (w_i \log x_i) \quad \text{Eq. 3}$$

in which: w_i is the mass fraction of the class in relation to the mass of the total sample and *xi* is the mean diameter between aggregate classes *i* (mm). The stable aggregates index (SAI_W) and the percentage of aggregates >2.0 mm ($AGRI_W$) derived from wet sieving were obtained according to Castro Filho et al. (1998) and Wendling et al. (2005) with the following equations:

$$SAI_W = [(W_S - w_p < 0.105)/W_S] \times 100 \quad \text{Eq. 4}$$

$$AGRI_W = (W_u > 2) \times 100 \quad \text{Eq. 5}$$

in which: W_S is the sample weight (g); w_p <0.105 is the weight of the aggregates of the class <0.105 mm (g); and *Wu* is the proportion of stable aggregates >2 mm in water. For the calculation of indices (MWD_W, GMD_W, SAI_W, and $AGRI_W$), the amount of particles >2.0 mm (grit) was discounted from the dry weight of aggregates retained in the class 4.75 – 2.00 mm (Castro Filho et al., 1998).

Soil chemical analysis

Among the chemical properties, the pH in H_2O was determined potentiometrically using a soil:water (1:2.5) suspension. Phosphorous and K were extracted by Mehlich-1 and determined by molecular absorption and flame photometry (Defelipo and Ribeiro, 1997). The Ca^{2+}, Mg^{2+}, and Al^{3+} contents were extracted with KCl 1 mol L^{-1} and determined by

Table 1. Details of the treatments used in the rehabilitated area after bauxite mining with coffee cultivation and intercropping cover crops subjected to different fertilization procedures

Fertilization (plots)	
NF	No manure or fertilizer application.
OF	50 Mg ha^{-1} (dry basis) of poultry manure (1/2 dose applied to the planting furrow and 1/2 cast between the rows).
CF	8 Mg ha^{-1} of dolomitic limestone with 80 % PRNT, with 1/3 of the dose applied to the planting furrow and the remaining 2/3 between the rows. Additionally, 1.5 Mg ha^{-1} of Bayovar natural reactive phosphate was applied to the bottom of the furrow and 0.70 ha^{-1} between the rows.
OF+CF	The final treatment combined the aforementioned OF+CF. After planting the coffee, OF+CF and CF fertilization schemes were conducted, and from the second year, coffee production fertilizers were applied, both as blanket fertilizers in the planting rows using NPK fertilizers on 20-05-20 and in similar doses (600 g $plant^{-1}$, divided into two applications during the growing season) among the treatments.
Ground covers (subplots)	
NP	In which pre-emergent herbicide was applied when necessary.
B	Brachiaria brizantha, cv. Piatã (25 kg ha^{-1} of viable seeds).
S	A mixture of seeds from two species: 80 % Stylosanthes capitata and 20 % Stylosanthes macrocephala, 2.5 kg ha^{-1} of viable seeds.
NV	The adjacent area, covered by a fragment of NV defined as a Seasonal Semi-deciduous Montane Forest (IEF, 2016), was considered in this study as a reference area, although it was not previously part of the described design.

NF: no fertilization; OF: organic; CF: chemical; OF+CF: organic + chemical; NP: no plants; B: Brachiaria grass; S: stylosanthes; NV: native vegetation. PRNT: relative power of total neutralization; NPK: Nitrogen; Phosphorus and Potassium.

atomic absorption and flame photometry. The potential acidity (H+Al) was extracted with calcium acetate 0.5 mol L^{-1} at pH 7 and determined by tritation (Donagemma et al., 2011). The remaining P (P-rem) content in the equilibrium solution was determined after 1 h of agitation of a solution with P 60 mg L^{-1} in $CaCl_2$ 0.01 mol L^{-1}, in a soil:solution ratio of 1:10 and determined by molecular absorption (Alvarez V et al., 2000). The results of the sortive complex analysis allowed the calculation of the base sum (BS = Ca^{2+} + Mg^{2+} + K^+ + Al^{3+}), cation-exchange capacity in pH 7 (CEC = BS + H + Al), effective cation-exchange capacity (t = BS + Al^{3+}), saturation by aluminum (m = 100×Al^{3+}/t), and base saturation (V = 100×BS/CEC).

Analysis of the organic properties

In the analysis of organic properties, the total organic C and N contents and the organic matter fractions in soil samples were measured alongside obtaining three classes of stable aggregates by dry sieving: macroaggregates (4.75 – 2.00 mm), mesoaggregates (2.00 – 0.25 mm), and microaggregates (0.25 – 0.053 mm) (Costa Junior et al., 2011, 2012; Cavalcante et al., 2019). The total organic carbon (TOC) and total nitrogen (TN) of the soil were determined, respectively, by wet oxidation methods with external heating (Yeomans and Bremner, 1988) and sulfuric digestion followed by distillation (Kjeldahl) (Tedesco, 1985). Labile organic C (LOC) was determined according to the procedure proposed by Blair et al. (1995), which was adapted for tropical soils by Shang and Tiessen, (1997). The determination of labile N (LN) was performed by adapting the Sahrawat (1982) method.

In the physical fractionation of SOM (Sohi et al., 2001), the free light organic matter (LOM_L) fraction was obtained with the densimetric method; the coarse (POM_C) and fine (POM_F) particulate organic matter and mineral associated organic matter (MOM) fractions were determined with granulometric fractionation. The LOM_L separation was performed through the centrifugation of 5 g of fine air-dried soil in triplicate, preceded by manual agitation with NaI (d = 1.60 g cm^{-3}); the supernatant with LOM_L was slowly filtered with the aid of a vacuum pump, thus separating the LOM_L from the NaI solution. The C and N contents of the LOM_L fraction were determined by dry combustion in a CHNS elemental analyzer (Perkin Elmer). The remaining soil material (heavy fraction - HF) was sifted using 0.210- and 0.053-mm sieves, yielding coarse POM (POM_C, 2.00 –0.210 mm) and fine POM (POM_F, 0.210 – 0.053 mm) fractions. After drying, the organic C and total N contents of these fractions were determined according to Yeomans and Bremner (1988) and Tedesco (1985), respectively. The C and N contents of the mineral associated organic matter (MOM) were calculated by the difference between the total soil C and N and the organic fractions: LOM_L+POM_C+POM_F.

Soil quality index (SQI)

The SQI was developed based on principal component analysis (PCA), to evaluate the effect of different management systems on the rehabilitation of the bauxite-mined area. Methodologies used by Karlen and Stott (1994) and Brejda et al. (2000) were adapted for this purpose, following the procedure proposed by Cavalcante et al. (2021).

The following steps were performed: *a*) 37 properties (original variables that play important roles in the soil) of the management systems and reference area were initially selected; *b*) a normality hypothesis test was conducted using the Lilliefors test (p<0.10); *c*) the data that presented a normal distribution were submitted to a multicollinearity test with the traditional trail analysis method (Cruz and Carneiro, 2006), with the exclusion of highly correlated variables, that is, to verify the presence or absence of dependencies between the variables. The multicollinearity diagnostic was made using the variance inflation factor (VIF) method using statistical software, in which VIF values greater than 10 were considered (Hair et al., 2009); *d)* PCA was then performed as a method of factor extraction, to only interpret the factors that presented eigenvalues >1.0. The retained factors were submitted to the varimax rotation to maximize the relation between independent attributes. In each principal component, only variables with high factor loadings were retained, i.e., those with absolute values within 10 % of the highest factor loading (Andrews et al., 2002), so that in the end, properties representative of the physical, chemical, and organic soil quality were selected; *h*) the selected properties were submitted a new varimax rotation and the respective rotated factor loadings were used in the calculation of the relative weights of the attributes on SQI, according to the following equation:

$$W_i = \frac{F_1 P_{1i} + F_2 P_{2i}}{(\sum_{j=1}^{n} F_1 P_{1j}) + (\sum_{j=1}^{n} F_2 P_{2j})} \qquad \text{Eq. 6}$$

in which: Wi is the relative weight of the *i*-th variable in SQI; F_{1i} and F_{2i} are the eigenvalues of the principal components; Pi is the rotational factorial loading of the *i*-th variable; Pj is the rotational factorial loading of the *j*-th variable; *i* and *j* are indices for the variables; and n is the number of variables involved in the PCA. After the selection of the indicators, the values of each variable were normalized by means of a relative standardization to be included in the SQI, being transformed into scores of the indicators (S), from 0 to 1, according to Liebig et al. (2001) and Bhardwaj et al. (2011). The SQI was determined as:

$$SQI = \sum_{i=1}^{n} (W_i \times S_i) \qquad \text{Eq. 7}$$

in which: SQI is a number from 0 to 1; W_i is the PC weighting factor, a number between 0 to 1; and S_i is the indicator score for variable *i*, a number between 0 to 1. Higher scores in the model indicated a better soil quality or greater performance of soil function.

Statistical analysis

Two-way ANOVA was used to check the effects of fertilization, ground covers, and their interactions on organic fractions in different aggregate-size classes of soils in bauxite mining areas undergoing rehabilitation. Tukey's HSD post hoc test at p<0.05 was used to evaluate the differences between the means. The PCA loaded variables were subject to Pearson correlation analysis at p<0.01, p<0.05, and p<0.10. The data were analyzed using the Microsoft Excel XLSTAT software (version 2021.3.1) (Addinsoft, 2021).

RESULTS

Effect of management systems on C and N pools

The interaction between fertilization and cover crops was not observed in the soil (Table 2). Significant effect of fertilization was observed in the TOC, TN, C-MOM, N-LOM_L, N-POM_C, N-MOM contents, and C-LOM_L, C-POM_C, C-MOM, N-LOM_L, N-POM_C contents in the cover crops. The OF+CF fertilization contributed to the increase of these contents in soil, differing from NF, although having been equivalent to OF and CF (Table 3). However, the OF and CF fertilization treatments contributed to the higher N contents in LOM_L. Brachiaria grass (B) increased C and N contents in the soil and soil fractions regarding the subplots without plants (Table 3). While the use of Stylosanthes (S), despite contributing to improve of C and N contents, did not statistically differ from areas without plants (NP).

Selection of minimum data set

Among the 37 selected variables for the selection of the minimum data set (Table 4), 18 did not present deviations following the normal distribution (Organic: C-LOM_L, C-POM_C,

Table 2. ANOVA results for the effects of fertilization, cover crops and their interaction on C and N fractions in different aggregate size classes of soils in bauxite mining area subjected to rehabilitation

Variance source	Degree of freedom		TOC	TN	C-LOM_L	C-POM_C	C-POM_F	C-MOM	N-LOM_L	N-POM_C	N-POM_F	N-MOM
							Soil					
Fertilization	3		0.015*	0.023*	0.333	0.317	0.545	0.005*	0.007*	0.002*	0.121	0.028*
Cover	2	P-Value	0.010*	0.070	<0.0001*	0.005*	0.155	0.014*	<0.0001*	0.036*	0.124	0.081
Fertilization x Cover	6		0.890	0.974	0.057	0.178	0.567	0.828	0.510	0.871	0.625	0.969
							Macroaggregates					
Fertilization	3		0.453	0.094	0.458	0.131	0.899	0.320	0.572	0.010*	0.877	0.044*
Cover	2	P-Value	0.303	0.142	0.007*	0.060	0.096	0.786	0.017*	0.030*	0.091	0.308
Fertilization x Cover	6		0.837	0.916	0.423	0.644	0.839	0.451	0.588	0.734	0.908	0.776
							Mesoaggregates					
Fertilization	3		0.302	0.101	0.626	0.015*	0.056	0.050*	0.235	0.104	0.708	0.050*
Cover	2	P-Value	0.175	0.230	0.002*	0.228	0.179	0.177	0.0004*	0.888	0.301	0.225
Fertilization x Cover	6		0.928	0.956	0.867	0.166	0.513	0.753	0.566	0.698	0.799	0.922
							Microaggregates					
Fertilization	3		0.162	0.058	0.909	<0.0001*	0.001*	0.068	0.853	0.368	0.015*	0.038*
Cover	2	P-Value	0.167	0.248	0.011*	0.880	0.522	0.159	0.022*	0.636	0.597	0.288
Fertilization x Cover	6		0.852	0.987	0.995	0.488	0.968	0.714	0.914	0.877	0.273	0.937

TOC: total organic carbon; TN: total nitrogen; LOM_L: free light organic matter; POM_C: coarse particulate organic matter; POM_F: fine particulate organic matter; and MOM: mineral-associated organic matter. (*) Indicates a significant effect determined with Tukey's test at p<0.05.

Table 3. Carbon and N fractions in soil and in different aggregate size classes of soil under natural forest and in a rehabilitated bauxite mining areas with fertilization and cover crops

Fractions	NV	Fertilization				Ground cover		
		NF	OF	CF	OF + CF	NP	B	S
				Soil (g kg^{-1})				
TOC	65.364	14.324 **B**	17.257 **AB**	17.335 **AB**	19.482 **A**	15.081 **b**	19.287 **a**	16.930 **ab**
TN	5.337	0.954 **B**	1.244 **AB**	1.084 **AB**	1.322 **A**	1.029 **a**	1.283 **a**	1.142 **a**
C-LOM_L	0.084	0.013 **A**	0.033 **A**	0.032 **A**	0.010 **A**	0.003 **b**	0.051 **a**	0.013 **b**
C-POM_C	1.471	0.197 **A**	0.306 **A**	0.232 **A**	0.313 **A**	0.226 **b**	0.386 **a**	0.173 **b**
C-MOM	60.785	12.582 **B**	15.393 **AB**	15.867 **AB**	17.875 **A**	13.523 **b**	17.257 **a**	15.506 **ab**
N-LOM_L	0.005	0.0005 **B**	0.0018 **A**	0.0017 **A**	0.0006 **AB**	0.0002 **b**	0.0025 **a**	0.0008 **b**
N-POM_C	0.073	0.011 **B**	0.017 **AB**	0.011 **B**	0.021 **A**	0.013 **ab**	0.019 **a**	0.013 **a**
N-MOM	5.152	0.925 **B**	1.197 **AB**	1.046 **AB**	1.266 **A**	0.992 **a**	1.228 **a**	1.106 **a**
				Macroaggregates (g kg^{-1})				
C-LOM_L	0.203	0.007 **A**	0.030 **A**	0.020 **A**	0.011 **A**	0.003 **b**	0.043 **a**	0.005 **b**
N-LOM_L	0.010	0.0001 **A**	0.0006 **A**	0.0006 **A**	0.0004 **A**	0.0001 **b**	0.0010 **a**	0.0002 **ab**
N-POM_C	1.454	0.070 **B**	0.122 **AB**	0.130 **A**	0.080 **AB**	0.076 **b**	0.125 **a**	0.101 **ab**
N-MOM	2.632	0.683 **B**	0.794 **AB**	0.705 **AB**	0.956 **A**	0.725 **a**	0.858 **a**	0.762 **a**
				Mesoaggregates (g kg^{-1})				
C-LOM_L	1.132	0.048 **A**	0.064 **A**	0.040 **A**	0.018 **A**	0.006 **b**	0.111 **a**	0.011 **b**
C-POM_C	3.887	0.750 **AB**	1.158 **A**	0.561 **B**	0.463 **B**	0.803 **a**	0.853 **a**	0.543 **a**
C-MOM	53.272	12.435 **B**	13.425 **AB**	14.687 **AB**	15.764 **A**	13.095 **a**	15.110 **a**	14.029 **a**
N-LOM_L	0.054	0.0012 **A**	0.0029 **A**	0.0013 **A**	0.0007 **A**	0.0002 **b**	0.0039 **a**	0.0004 **b**
N-MOM	4.160	0.759 **B**	0.921 **AB**	0.873 **AB**	1.049 **A**	0.825 **a**	0.982 **a**	0.894 **a**
				Microaggregates (g kg^{-1})				
C-LOM_L	0.171	0.008 **A**	0.006 **A**	0.010 **A**	0.009 **A**	0.002 **b**	0.016 **a**	0.008 **ab**
C-POM_C	0.031	0.017 **B**	0.132 **A**	0.023 **B**	0.017 **B**	0.051 **a**	0.046 **a**	0.045 **a**
C-POM_F	3.241	0.867 **B**	1.794 **A**	0.962 **B**	0.870 **B**	1.003 **a**	1.244 **a**	1.123 **a**
N-LOM_L	0.009	0.0003 **A**	0.0002 **A**	0.0002 **A**	0.0003 **A**	0.00002 **b**	0.00041 **a**	0.00028 **ab**
N-POM_F	0.189	0.074 **AB**	0.108 **A**	0.066 **AB**	0.055 **B**	0.071 **a**	0.084 **a**	0.072 **a**
N-MOM	3.767	0.686 **B**	0.857 **AB**	0.798 **AB**	0.993 **A**	0.757 **a**	0.897 **a**	0.847 **a**

NF: no fertilization; OF: organic; CF: chemical; OF+CF: organic + chemical; NP: no plants; B: Brachiaria grass; S: stylosanthes; TOC: total organic carbon; TN: total nitrogen; LOM_L: free light organic matter; POM_C: coarse particulate organic matter; POM_F: fine particulate organic matter; MOM: mineral-associated organic matter. The means are followed by the same letter(s) within each line, which do not significantly differ from $p<0.05$ by Tukey's test.

LN, N-LOM_L, N-POM_C, N-POM_F, and N-MOM; Chemical: P, K, Mg^{2+}, Al^{3+}, H+Al, and m; Physical: $Sand_C$, $Sand_F$, Silt, Clay and TP), these were eliminated from the process.

According to the trail analysis method performed through the multicollinearity test, the diagnosis for the explanatory variables revealed that of the 19 soil parameters, 11 did not present multicollinearity (Organic: LOC, C-POM_F, and C-MOM; Chemical: pH, Ca^{2+}, t, and P-rem; Physical: BD, Micro, $AGRI_W$, and SAI_W) (Table 5). A high frequency of correlations indicates that organic, chemical, and physical soil properties can be organized into factors based on their correlation structures. However, not all parameters correlated with each other, namely in the case of C-POM_F and BD (Table 6). In general, the C-MOM, pH, Ca^{2+}, t, P-rem, Micro, and SAI_W were positively correlated with most soil properties, while in contrast, $AGRI_W$ was negatively correlated with C-POM_F.

The three first factors had eigenvalues exceeding one, and 89.61 % of the total variance were explained by three principal components (PCs), being retained for interpretation (Table 7). The factors explained more than 90 % of the variation in C-MOM, t, and SAI_W,

Table 4. Means of the physical, chemical, and organic properties of the soil (0.00-0.20 m) in native forests and in a rehabilitated area after bauxite mining cultivated with coffee and intercropping cover crops subjected to different fertilization procedures

Property	Unit	NV	No Fertilization			Organic fertilization			Chemical fertilization			Organic + chemical fertilization			Lilliefors test
			NP	B	S	NP	B	S	NP	B	S	NP	B	S	P-value
TOC	g kg^{-1}	65.36	12.42	16.57	13.98	14.05	19.54	18.18	15.22	18.93	17.85	18.62	22.11	17.71	0.985
LOC	g kg^{-1}	4.33	0.64	0.84	0.79	0.68	1.25	0.95	0.87	1.24	0.92	1.02	1.44	0.98	0.785
C-LOM$_L$	g kg^{-1}	0.0842	0.0017	0.0296	0.0090	0.0052	0.0732	0.0221	0.0017	0.0844	0.0113	0.0043	0.0178	0.0082	< 0.0001*
C-POM$_C$	g kg^{-1}	1.47	0.19	0.22	0.19	0.32	0.44	0.16	0.14	0.31	0.25	0.26	0.58	0.10	0.002*
C-POM$_F$	g kg^{-1}	3.02	1.36	1.54	1.69	1.50	1.58	1.53	1.20	1.75	0.80	1.25	1.72	1.03	0.786
C-MOM	g kg^{-1}	60.79	10.88	14.78	12.09	12.22	17.45	16.51	13.88	16.86	16.86	17.11	19.94	16.57	0.927
TN	g kg^{-1}	5.34	0.87	1.07	0.92	1.07	1.37	1.30	0.92	1.20	1.13	1.26	1.49	1.22	0.221
LN	g kg^{-1}	0.130	0.033	0.035	0.031	0.038	0.049	0.047	0.038	0.050	0.035	0.054	0.054	0.047	0.067*
N-LOM$_L$	g kg^{-1}	0.0053	0.0001	0.0009	0.0004	0.0004	0.0038	0.0013	0.0001	0.0044	0.0007	0.0003	0.0009	0.0008	< 0.0001*
N-POM$_C$	g kg^{-1}	0.0727	0.0084	0.0141	0.0094	0.0125	0.0226	0.0152	0.0095	0.0156	0.0081	0.0223	0.0223	0.0179	0.002*
N-POM$_F$	g kg^{-1}	0.1065	0.0163	0.0186	0.0191	0.0218	0.0363	0.0269	0.0176	0.0428	0.0157	0.0378	0.0375	0.0290	< 0.0001*
N-MOM	g kg^{-1}	5.15	0.84	1.04	0.89	1.03	1.30	1.25	0.89	1.14	1.11	1.20	1.43	1.17	0.077*
pH(H_2O)	1;2.5	5.10	4.90	5.33	5.16	5.77	6.44	5.63	6.02	6.43	6.11	6.59	6.56	6.37	0.181
P	mg kg^{-1}	6.92	1.48	1.60	1.24	24.77	36.86	18.58	39.04	21.03	10.99	62.51	42.37	58.92	< 0.0001*
K	mg kg^{-1}	58.65	5.90	41.88	21.28	30.72	367.36	82.24	28.28	270.58	77.68	128.59	283.50	118.70	< 0.0001*
Ca^{2+}	cmol$_c$ kg^{-1}	0.45	0.42	0.76	0.35	2.42	3.11	2.05	3.46	3.69	2.96	5.35	4.21	4.68	0.269
Mg^{2+}	cmol$_c$ kg^{-1}	0.31	0.12	0.28	0.11	0.55	0.78	0.45	0.53	1.29	0.59	1.03	0.84	0.88	0.007*
Al^{3+}	cmol$_c$ kg^{-1}	1.64	0.20	0.15	0.27	0.00	0.00	0.22	0.00	0.00	0.04	0.04	0.09	0.00	< 0.0001*
H + Al	cmol$_c$ kg^{-1}	16.96	6.62	6.85	6.82	5.16	3.69	6.64	4.36	3.33	4.78	3.65	4.28	3.86	0.041*
BS	cmol$_c$ dm^{-3}	0.89	0.42	0.92	0.38	2.38	3.78	2.10	3.13	4.40	2.89	4.96	4.58	4.41	0.506
CEC	cmol$_c$ dm^{-3}	2.50	0.56	1.04	0.58	2.38	3.78	2.27	3.13	4.40	2.91	4.99	4.65	4.41	0.428
t	cmol$_c$ dm^{-3}	17.52	5.47	6.39	5.51	6.41	6.65	7.25	6.48	6.97	6.56	7.66	7.98	7.31	0.640
V	%	5.10	6.95	12.10	6.60	37.50	56.75	32.20	47.83	61.03	47.10	65.13	57.45	58.73	0.115
m	%	64.50	33.58	13.43	36.43	0.00	0.00	11.55	0.00	0.00	1.25	0.73	3.15	0.00	< 0.0001*
P-rem	mg L^{-1}	14.25	6.00	7.73	6.85	8.23	11.3	8.63	10.00	9.65	7.78	10.73	10.38	9.83	0.370
Sand$_C$	g kg^{-1}	165.0	110.0	117.5	135.0	112.5	97.5	130.0	130.0	107.5	105.0	142.5	107.5	112.5	< 0.0001*
Sand$_F$	g kg^{-1}	195.0	122.5	135.0	155.0	140.0	105.0	142.5	140.0	127.5	132.5	155.0	127.5	120.0	0.001*
Silt	g kg^{-1}	105	77	90	70	78	78	73	108	108	105	143	113	93	0.059*
Clay	g kg^{-1}	535	690	658	640	670	720	655	622	657	657	560	652	675	< 0.0001*
BD	kg dm^{-3}	1.02	1.31	1.25	1.33	1.28	1.28	1.29	1.3	1.29	1.3	1.35	1.26	1.33	0.490
Macro	dm^3 dm^{-3}	0.27	0.18	0.18	0.16	0.19	0.18	0.16	0.18	0.16	0.15	0.17	0.13	0.13	0.787
Micro	dm^3 dm^{-3}	0.29	0.35	0.35	0.34	0.33	0.34	0.36	0.33	0.35	0.36	0.36	0.37	0.36	0.208
TP	dm^3 dm^{-3}	0.56	0.53	0.53	0.50	0.52	0.52	0.52	0.51	0.51	0.51	0.48	0.51	0.49	0.024*
MWD$_W$	mm	3.08	2.99	2.71	2.74	2.56	2.86	2.47	2.52	2.46	2.54	2.51	2.50	2.58	0.978
GMD$_W$	mm	2.45	2.39	1.68	1.79	1.58	2.02	1.46	1.28	1.38	1.40	1.50	1.44	1.68	0.260
AGRI$_W$	%	89.87	85.33	76.62	77.11	70.25	81.48	66.44	71.78	67.31	71.17	67.85	68.81	69.69	0.429
SAI$_W$	%	92.45	93.79	83.05	85.52	83.39	89.21	83.20	72.71	78.48	77.09	82.80	80.94	86.95	0.605

* The variable from which the sample was extracted does not follow the normal distribution according to the Lilliefors test at <0.05; ns: not significant; NV: native vegetation; NP: no plants; B: Brachiaria; S: stylosanthes; TOC: total organic carbon; LOC: labile organic carbon; TN: total nitrogen; LN: labile nitrogen; LOM$_L$: free light organic matter; POM$_C$: coarse particulate organic matter; POM$_F$: fine particulate organic matter; MOM: mineral-associated organic matter; BS: base sum; CEC: cation-exchange capacity; t: effective cation-exchange capacity; V: base saturation; m: saturation by aluminium; P-rem: P remaining; Sand$_C$: coarse sand; Sand$_F$: fine sand; BD: bulk density; Macro: macroporosity; Micro: microporosity; TP: total porosity; MWD$_W$: mean weight diameter obtained by wet sieving; GMD$_W$: geometric mean diameter obtained by wet sieving; AGRI$_W$: percentage of water stable aggregates >2 mm; SAI$_W$: stable aggregates index in water.

Table 5. Multicollinearity diagnostic for the explanatory variables, based on the variance inflation factor (VIF), of management systems evaluated at 0.00-0.20 m soil layer

1	TOC	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	BS	CEC	t	V	P-rem	BD	Macro	Micro	MWD$_W$	GMD$_W$	AGRI$_W$	SAI$_W$
	1008	5	**28**	**961**	**16**	**13**	**86**	**886**	**939**	**12**	**40**	5	**15**	**25**	10	**664**	**89**	**387**	**25**
2	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	BS	CEC	t	V	P-rem	BD	Macro	Micro	MWD$_W$	GMD$_W$	AGRI$_W$	SAI$_W$	
	5	5	**11**	**15**	**13**	**82**	**722**	**852**	**11**	**39**	5	**15**	**24**	9	**630**	**89**	**358**	**23**	
3	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	BS	t	V	P-rem	BD	Macro	Micro	MWD$_W$	GMD$_W$	AGRI$_W$	SAI$_W$		
	5	4	**11**	**15**	**13**	**74**	**95**	**11**	**38**	5	**15**	**24**	9	**627**	**88**	**357**	**23**		
4	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	BS	t	V	P-rem	BD	Macro	Micro	GMD$_W$	AGRI$_W$	SAI$_W$			
	4	3	**11**	**15**	**13**	**72**	**95**	**11**	**38**	5	**12**	**19**	7	**53**	**15**	**21**			
5	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	t	V	P-rem	BD	Macro	Micro	MWD$_W$	AGRI$_W$	SAI$_W$				
	3	3	**11**	**14**	**13**	**23**	**11**	**35**	4	**11**	**17**	7	**48**	**15**	**17**				
6	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	t	V	P-rem	BD	Macro	Micro	AGRI$_W$	SAI$_W$					
	3	3	**11**	**14**	**13**	**23**	**11**	**35**	4	**11**	**17**	7	3	3					
7	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	t	P-rem	BD	Macro	Micro	AGRI$_W$	SAI$_W$						
	3	3	10	**14**	7	8	6	4	**11**	**17**	6	3	3						
8	LOC	C-POM$_F$	C-MOM	TN	pH	Ca^{2+}	t	P-rem	BD	Micro	AGRI$_W$	SAI$_W$							
	3	3	10	**14**	7	8	6	4	1	2	3	2							
9	LOC	C-POM$_F$	C-MOM	pH	Ca^{2+}	t	P-rem	BD	Micro	AGRI$_W$	SAI$_W$								
	3	2	7	7	8	5	4	1	2	3	2								

Bold numbers indicate variables that presented VIF >10. TOC: total organic carbon; LOC: labile organic carbon; TN: total nitrogen; POM$_F$: fine particulate organic matter; MOM: mineral-associated organic matter; BS: base sum; CEC: cation-exchange capacity; t: effective cation-exchange capacity; V: base saturation; P-rem: remaining; BD: bulk density; Macro: macroporosity; Micro: microporosity; MWD$_W$: mean weight diameter obtained by wet sieving; GMD$_W$: geometric mean diameter obtained by wet sieving; AGRI$_W$: percentage of water stable aggregates >2 mm; SAI$_W$: stable aggregates index in water.

Table 6. Pearson correlation coefficients between soil properties, evaluated for 0.00-0.20 m soil layer, in areas of natural forest and bauxite mining undergoing rehabilitation procedures and being cultivated with coffee and intercropping cover crop with different treatments of fertilization

Soil properties	LOC	C-POM$_F$	C-MOM	pH	Ca^{2+}	t	P-rem	BD	Micro	AGRI$_W$	SAI$_W$
LOC	1										
C-POM$_F$	0.312	1									
C-MOM	0.901*	-0.001	1								
pH	0.787*	-0.132	0.827*	1							
Ca^{2+}	0.643**	-0.267	0.731*	0.954*	1						
t	0.731*	-0.022	0.877*	0.820*	0.844*	1					
P-rem	0.762*	0.046	0.746*	0.906*	0.856*	0.766*	1				
BD	-0.245	-0.444	-0.185	0.081	0.253	-0.041	0.011	1			
Micro	0.547***	-0.042	0.711*	0.315	0.317	0.646**	0.149	-0.080	1		
AGRI$_W$	-0.353	0.086	-0.529***	-0.575***	-0.643**	-0.744*	-0.429	-0.092	-0.415	1	
SAI$_W$	-0.224	0.191	-0.305	-0.391	-0.389	-0.324	-0.295	0.123	-0.014	0.650**	1

*, ** and **: significant at $p<0.01$, $p<0.05$ and $p<0.10$, respectively.

80 % in LOC, C-POM$_F$, pH, P-rem, and BD, and 60 to 70 % in Micro and AGRI$_W$, respectively (Table 7). These properties are relevant to both agronomic and environmental studies, since they provide information about soil processes or its behavior (e.g., LOC, C-MOM, and pH). Other properties are equally important, namely those that indicate the capacity of the soil to resist cation exchange (e.g., t) and those that establish fundamental relationships with hydrological processes, as well as providing an essential function in the supply and storage of water, nutrients, and oxygen in the soil (e.g., BD).

During the PCA analysis, the indicators were selected and the weights (W_i) of each variable were calculated as a function of the eigenvalues and the explicability of the indicator by the retained factor (Table 8). The weights of the selected properties ranged from 0.07 to 0.21. The soil properties that had higher W_i values in SQI were those linked to organic and chemical indicators and those properties characterized by lower W_i values were linked to physical indicators.

Table 7. Rotated factor loadings and communalities of a three-factor model of organic, chemical, and physical soil properties in a bauxite mining area under rehabilitation and cultivated with coffee and intercropping cover crops with fertilization treatments

Indicator groups	Soil properties	Factor			Communalities
		1	2	3	
Organic	LOC	**0.89**	-0.32	-0.08	0.91
	C-POM_F	0.06	**-0.80**	0.18	0.67
	C-MOM	**0.94**	-0.12	-0.18	0.93
Chemical	pH	**0.86**	0.17	-0.36	0.90
	Ca^{2+}	0.81	0.37	-0.38	0.93
	t	**0.90**	0.03	-0.30	0.90
	P-rem	**0.81**	0.05	-0.28	0.73
Physical	BD	0.00	**0.87**	0.13	0.78
	Micro	**0.67**	-0.08	0.14	0.47
	$AGRI_W$	-0.47	-0.11	**0.70**	0.73
	SAI_W	-0.09	0.03	**0.95**	0.91
	Eigenvalues	5.92	1.79	1.15	
	Variability (%)	47.35	15.50	17.76	
	% Accumulated	47.35	62.85	80.61	

LOC: labile organic carbon; POM_F: fine particulate organic matter; MOM: mineral-associated organic matter; t: effective cation-exchange capacity; P-rem: P remaining; BD: bulk density; Micro: microporosity; $AGRI_W$: percentage of water stable aggregates >2 mm; SAI_W: stable aggregates index in water. The bold factors are considered highly loaded and included in the index.

Table 8. Organic and chemical properties selected as soil quality indicators of soils from 0.00-0.20 m soil layer, their rotational factor loads and weights in the soil quality index (SQI) of areas covered with native forests and after three years of recovery with coffee using different fertilization treatments and cover crops

Indicator groups	Soil properties	Factor		W_i
		1	2	
Organic	LOC	**0.89**	-0.21	0.20
	C-MOM	**0.95**	-0.14	0.21
Chemical	pH	**0.94**	0.14	0.21
	t	**0.92**	0.03	0.20
Physical	BD	-0.04	**0.99**	0.07
	SAI_W	**-0.42**	0.22	0.10
	Eigenvalues	3.64	1.07	
	Variability (%)	60.07	18.38	
	% Accumulated	60.07	78.46	

LOC: labile organic carbon; MOM: mineral-associated organic matter; t: effective cation-exchange capacity; BD: bulk density; SAI_W: stable aggregates index in water. Bold factors are considered highly loaded and included in the index.

DISCUSSION

Effect of management systems on soil organic properties

The use of inputs, whether of mineral or organic nature, can favor the increase of organic properties through different management practices, thus representing an important tool for the acquisition and maintenance of soil quality (Loss et al., 2009, 2011; Valadão et al., 2011; Cavalcante et al., 2019).

An increase in SOM due to herbaceous plants, principally those of the genus *Brachiaria*, has been observed in several papers (Pillon et al., 2011; Wendling et al., 2011; Carmo et al., 2012; Rossi et al., 2012; Cavalcante et al., 2019). The large number of roots incorporated into the soil by fast renovation and incorporating this grass, reflect the SOM contents and soil aggregation. It has been shown that stylosanthes, which present annual and bi-annual features and depend on restocking from natural sowing to remain in soils, presented a smaller contribution of C and N to soils through their root systems, thus limiting the recovery capacity of the soils. Thus, the effect of organic and chemical fertilization treatments on these variables is more strongly related to the development of herbaceous species, such as those that acquire their nutrient uptake through rich root systems and N_2 fixation (Silva and Corrêa, 2010; Barbosa et al., 2019), helping increase or maintain these properties in soils.

In general, the soil organic properties in areas with management systems were still lower than those observed in reference areas, that is, below the ideal condition of the reference considered in this research. However, the results showed that the properties essential for the proper functioning of the soil could be recovered through the adopted management practices.

Organic fraction distribution and its relationship with aggregate size

There was no significant interaction ($p>0.05$) between the fertilization treatments and the ground covers and the C, N, and SOM fractions in the evaluated aggregate classes, allowing for discussion of only the main effects of the treatments (Table 2). At 0.00–0.20 m soil layer, the rehabilitation alternatives influenced the distribution of organic compounds in the aggregate classes, showing that the restoration of vegetation promoted an increase in the organic contents and stability of the soil aggregates (Jiao et al., 2012; Raiesi, 2012; Deng and Shangguan, 2017). However, regardless of the treatment, the fractions obtained in the three structural classes were not equivalent or superior to those of NV, which had the highest values (Table 3). The greater contribution of plant waste and the fact that bauxite mining activities did not change the original condition of soil aggregation may be related to the results obtained in this situation. Changes in land management compromise soil quality (Deng and Shangguan, 2017). The results of management alternatives on the distribution of TOC and TN in the organic soil fractions were unique in each aggregate class (Table 2). In situations where there were significant differences ($p<0.05$), it was confirmed that the fertilization treatments alternated with regard to those that provided the highest C or N values in the studied aggregate classes. As for ground cover, in general, the Brachiaria (B) effectively ($p<0.05$) contributed to an increase in C and N contents in the fractions for which significant differences were observed in macro-, meso-, or microaggregates (Table 3). Stylosanthes (S) practically did not alter the fractions of organic matter in which they had significant differences ($p<0.05$), like the absence of plants.

Free light fraction (LOM_L) comprises the organic compartments most sensitive to soil degradation by farming (Freixo et al., 2002) and can be considered a premature indicator of the decline of SOM contents (Six et al., 2002; Wu et al., 2004; Lima et al., 2008; Pulrolnik et al., 2009; Santos et al., 2013). This fraction contains root fragments, seeds,

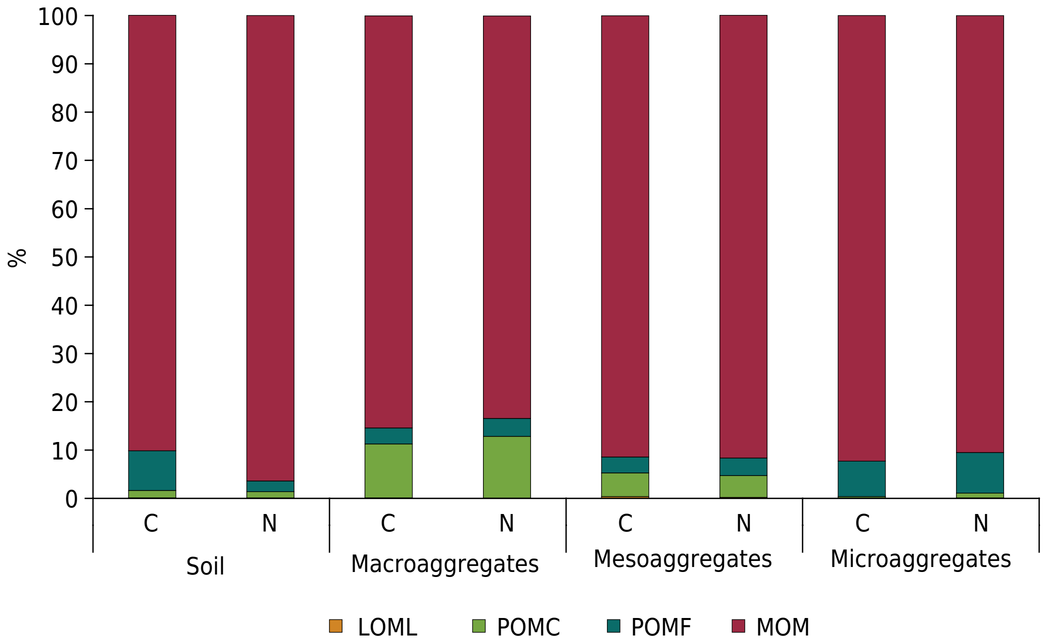

Figure 3. Carbon and nitrogen ratios of free light organic matter (LOM_L), coarse particulate organic matter (POM_C), fine particulate organic matter (POM_F), and mineral-associated organic matter (MOM) in soils and in aggregate size classes of soils from natural forest and a rehabilitated bauxite mining area subjected to different fertilization treatments and with different cover crops.

leaves, and twigs in the least advanced stages of decomposition, and it presents a significant seasonal and spatial variability since it is directly linked to the soil residue supply (Christensen, 2000). Among all the fractions, the LOM_L presented the lowest proportion of C and N (Figure 3). The highest C and N contents in the LOM_L fraction were found in the mesoaggregates, especially those that had received treatments consisting of fertilization and Brachiaria (OF/B, CF/B, and OF+CF/B). Loss et al. (2011) also observed a similar result. The incorporation of plant residues, either as a source of N or combined with the application of nitrogen fertilizers, contributed to higher percentages of C in mesoaggregates (Huang et al., 2015). In macroaggregates, there was a greater effect of N in all fractions. Better results of TN on macroaggregation have been observed (Hontoria et al., 2016). Among all the cases, the effect of CF fertilization was observed only in soil macroaggregates.

The OF led to higher values of C-POM_C in the mesoaggregates and C-POM_C, C-POM_F, and N-POM_F in the microaggregates, however, C-POM_C and N-POM_F in the meso- and microaggregates, respectively, which OF was like NF. These results confirm organic fertilization as an important management strategy to improve soil quality and highlight the importance of particulate fractions in evaluating soil quality. According to Rossi et al. (2012), the storage of C in particulate and light fractions is closely related to the recent input of vegetable residues, which supports the action of Brachiaria in maintaining these contents. According to the same authors, the particulate fraction may effectively indicate disturbances to land-use. Higher proportions of C and N of POM_C and POM_F were here found in the macro- and microaggregates, respectively (Figure 3). Huang et al. (2010) observed that the use of organic fertilization alone or in combination with inorganic fertilizer favored higher stocks of C-POM in soil microaggregates. The addition of nitrogen fertilizers may contribute to higher P contents in microaggregates (Wang et al., 2016). The difference in the proportions of free and particulate fractions observed in this study may have been related to mechanisms of the chemical stabilization of the SOM or to the degree of humification of the SOM in these fractions (Figure 2). Campos (2003) also revealed that the bigger the specific surface of the particle, the bigger its capacity to interact with organic matter. Accumulation of C in the particulate fraction and in the free fraction is closely associated with the recent supply of plant material (Rossi et al., 2012), which corroborates the action of Brachiaria in maintaining the soil C contents (Table 3). According to this same author, the particulate fraction may effectively indicate the differences between the use systems applied.

Among all the fractions, the highest C and N contents were found in MOM, in all aggregates classes, and with a contribution from all management systems (Figure 3). In the MOM fractions, the macro-, meso-, and microaggregates exhibited a similar behavior regarding the effect of fertilization, with higher values of N occurring in both classes of aggregates when a OF+CF fertilization procedure was used. This effect also was observed in C-MOM in the mesoaggregates. The dynamics of the MOM fraction would be closely related to the texture (Feller and Beare, 1997; Freixo et al., 2002) and the surface of the mineral particles (Campos, 2003). The largest proportion of C and N in this fraction could also be associated with the supply of organic matter, mainly by Brachiaria (Table 3), as suggested by Carmo et al. (2012). Santos et al. (2011) observed that the largest C contents in a native field area were associated with minerals, relating this effect to chemical protection mechanisms of organic matter with clay contents. Indeed, soils with low clay contents generally have smaller protection of organic matter and low capacity of the mineral fraction to keep a relative stock of C in MOM, leading to the vulnerability of the management system (Santos et al., 2013). However, the higher proportion of C and N in MOM indicates that the complexation mechanism had a higher relevance than the occlusion mechanism. Thus, MOM is the fraction most stable to management changes, being of great importance for the storage and availability of C and N in the soil.

Organic, chemical, and physical soil quality indicators

The SQI was significantly higher ($p<0.05$) for the NV (1.0 ± 0.03) than the other management systems (Figure 4). Higher SQI scores for preserved sites were previously found by Bhardwaj et al. (2011) and Chaves et al. (2017), who noted the alteration of soil properties when replaced by another management system with soil use intensity. The SQI values followed the order: OF+CF/B (0.78±0.04) > OF+CF/NP (0.74±0.04) > OF/B (0.72±0.03) = OF+CF/E (0.72±0.04) = CF/B (0.72±0.03) > OF/E (0.69±0.03) > CF/E (0.68±0.03) > CF/NP (0.65±0.03) > NF/B (0.64±0.03) = OF/NP (0.64 ±0.03) > NF/E (0.59 ±0.03) > NF/NP (0.58 ±0.03). The cover plants, mainly Brachiaria, helped significantly increase the soil quality when fertilized (Figure 4). The plots without plants (NP) presented SQI values equivalent to those of the stylosanthes. Santos et al. (2011) observed that higher C contents in soils and soil fractions were found in the superficial soil layer between rows of forest systems, due to the greater contribution of cultural residues. According to Pillon et al. (2011), the grasses used between the rows of coffee in the 0.00-0.20 m layer contributed to the supply of SOM to the surface and its redistribution in the subsurface.

The mean contribution of the variables to the SQI (0.00-0.20 m soil layer) followed this order: t (0.23 ± 0.01) > pH (0.20 ± 0.01) > SAI_W (0.08 ± 0.002) > C-MOM (0.07 ± 0.01) > LOC (0.06 ± 0.01) = BD (0.06 ± 0.01). The chemical variables showed a greater contribution to the SQI (Figure 4). The cation exchange capacity (CEC) is an indicator of soil fertility (Brady and Weil, 2007). The pH showed a significant positive correlation with t ($r = 0.820$; $p<0.01$) (Table 6), and it had a direct relationship with the availability of nutrients (Bohn et al., 2001). Mukhopadhyay et al. (2016) found a significant positive correlation between pH and CEC ($r = 0.937$; $p<0.01$) in the elaboration of the SQI for the assessment of recovered coal mine residues. The OF+CF/B management system contributed the most to the SQI values of t (0.27) and pH (0.22). OF/B and NF/NP treatments had significantly higher SAI_W values than all other similar rehabilitation systems studied (Cavalcante et al., 2019). Mbagwu and Schwertmann (2006) also showed that soils with high levels of Al oxides than Fe oxides favored soil

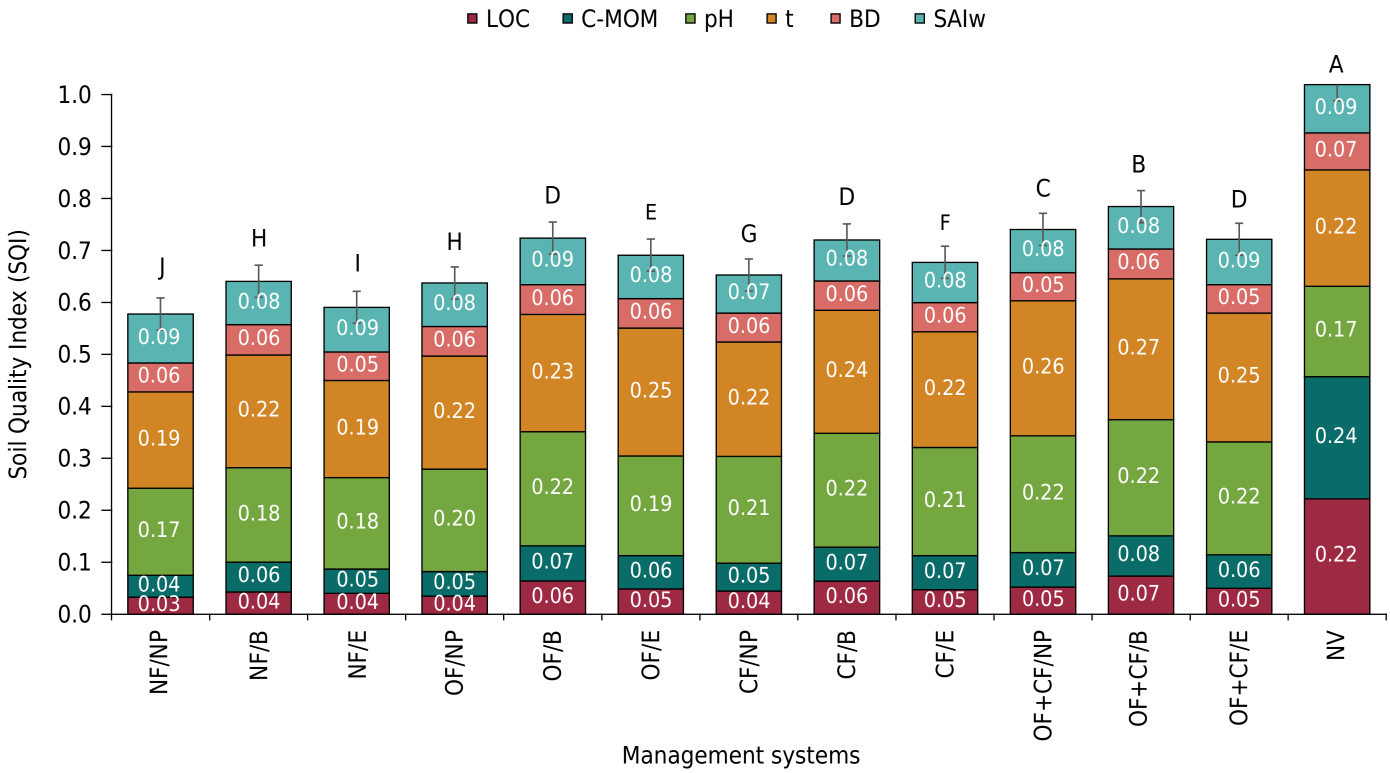

Figure 4. Soil quality index (SQI) means and contributions of each indicator in the SQI at 0.10-0.20 m soil layer, in areas covered with native forest and after three years of recovery with coffee using different fertilization treatments and ground cover plants. NF: no fertilization; OF: organic; CF: chemical; OF+CF: organic + chemical; NP: no plants; B: Brachiaria grass; S: stylosanthes; NV: native vegetation; LOC: labile organic carbon; MOM: mineral-associated organic matter; t: effective cation-exchange capacity; BD: bulk density; SAI_W: stable aggregates index in water.

macroaggregation. However, the alteration of management systems may reduce SOM levels and, consequently, the stability of aggregates.

In general, the proportions of C and N in different compartments of organic matter (LOM_L, POM_C, POM_F, and MOM) were smaller in the most labile fractions (LOM_L: C = 0.1 %, N = 0.1 %; POM_C : C = 1.5 %, N = 1.3 %; and POM_F: C = 8.2 %, N = 2.2 %), reflecting on the dynamics and availability of these nutrients in the soil (t x C-MOM: r = 0.877; p<0.01); comparatively the highest levels in MOM (C = 90.2 %; N = 96.4 %), whose dynamics would be closely related to texture (Feller and Beare, 1997; Freixo et al., 2002). The interaction between the organo-mineral complexes would also be directly related to the surface of the mineral particles, as mentioned earlier. Santos et al. (2011) noted higher C contents in soils associated with minerals, relating this effect to the mechanisms of chemical protection of organic matter with the levels of clay.

According to the results obtained by Cavalcante et al. (2019), there is a great positive correlation between the carbon management index (CMI) and LOC (r = 0.998; p<0.01). Thus, short-term LOC values can provide a sensitive indicator for changes in soil C dynamics through the adoption of management practices for the rehabilitation of mined areas. Bulk density has also been used as an indicator of soil quality, as this is a dynamic property that is susceptible to use and easy to determine, since it is related to compaction and the relative restriction to root growth (Arshad et al., 2002).

CONCLUSIONS

When organic (OF), chemical (CF), and OF+CF fertilizers were applied to areas cultivated with coffee intercropped with Brachiaria (B), they increased C and N contents in the soils and aggregates classes, as well as in compartments of SOM. The minimum set of soil quality indicators of reclaimed bauxite-mined areas could consist of organic indicators: labile organic carbon (LOC) and mineral-associated organic matter (C-MOM); chemical indicators: pH and effective cation-exchange capacity (t); and physical indicators: bulk density (BD) and stable aggregates index in water (SAI_W). The t and pH were the variables most sensitive to the management systems used in the rehabilitation of the mined area, and were thus considered the best indicators of soil quality. Brachiaria was the cover plant that contributed most to increasing the soil quality of mined bauxite areas by increasing the SQI, especially when fertilized. Thus, the use of fertilizers and ground cover plants intercropped with coffee in the bauxite-mined areas improved the soil's physical, chemical, and organic properties, providing a viable option for reconditioning mineral exploration areas.

ACKNOWLEDGMENTS

This research was supported by the CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico). The authors further gratefully acknowledge the Graduate Program in Soil and Plants Nutrition of UFV and the Brazilian Company of Aluminum – Votorantim Metais (CBA/VM) for the financial support.

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