SOIL PHYSICAL PROPERTIES OF HIGH MOUNTAIN FIELDS UNDER BAUXITE MINING

Propriedades físicas do solo de campos altimontanos sob interferência da mineração de bauxita

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ABSTRACT

Mining contributes to the life quality of contemporary society, but can generate significant impacts, these being mitigated due to environmental controls adopted. This study aimed to characterize soil physical properties in high-altitude areas affected by bauxite mining, and to edaphic factors responses to restoration techniques used to recover mined areas in Poços de Caldas plateau, MG, Brazil. The experiment used 3 randomized block design involving within 2 treatments (before mining intervention and after environmental recovery), and 4 replicates (N=24). In each treatment, soil samples with deformed structures were determined: granulometry, water-dispersible clay content, flocculation index, particle density, stoniness level, water aggregate stability, and organic matter contend. Soil samples with preserved structures were used to determine soil density and the total volume of pores, macropores, and micropores. Homogenization of stoniness between soil layers as a result of soil mobilization was observed after the mined area recovery. Stoniness decreased in 0.10-0.20 m layer after recovery, but was similar in the 0-0.10 m layer in before and after samples. The recovery techniques restored organic matter levels to pre-mining levels. However, changes in soil, including an increase in soil flocculation degree and a decrease in water-dispersible clays, were still apparent post-recovery. Furthermore, mining operations caused structural changes to the superficial layer of soil, as demonstrated by an increase in soil density and a decrease in total porosity and macroporosity. Decreases in the water stability of aggregates were observed after mining operations.

Index terms: Environmental recovery, physical soil quality, soil recovery.

RESUMO

A mineração contribui para a qualidade de vida da sociedade contemporânea, porém pode gerar impactos significativos, sendo esses mitigados em função dos controles ambientais adotados. Neste trabalho objetivou-se caracterizar as propriedades físicas do solo, mediante a influência de empreendimentos minerários, avaliando as respostas dos atributos edáficos frente às técnicas utilizadas para a recuperação de áreas degradadas pela mineração de bauxita na região do planalto de Poços de Caldas, MG. O delineamento experimental foi concebido com 3 blocos casualizados, com 2 tratamentos (antes da intervenção minerária e depois da recuperação ambiental), e 4 repetições (N=24). Em cada situação, por meio das amostras com estruturas deformadas foram determinados: granulometria, argila dispersa em água, índice de floculação, densidade de partículas, índice de pedregosidade, estabilidade de agregados em água e teor total de matéria orgânica, por meio das amostras com estrutura preservada foram determinadas: densidade do solo, volume total de poros, macroporos e microporos. Após a recuperação da área minerada, ocorreu homogeneização da pedregosidade entre as camadas, decorrente do revolvimento e, consequentemente, da sua redução na camada de 0,10 a 0,20 m; os processos de recuperação da área minerada propiciaram manutenção dos teores de matéria orgânica, aumento do grau de floculação do solo e redução da argila dispersa em água; a intervenção minerária proporcionou alterações estruturais na camada superficial do solo, evidenciadas pelo aumento na sua densidade, redução na porosidade total e macroporosidade; houve redução da estabilidade de agregados em água após a intervenção minerária.

Termos para indexação: Recuperação ambiental, qualidade física do solo, recuperação do solo.

(Received in may 6, 2013 and approved in june 27, 2013)

INTRODUCTION

Mining is an important contributor to the improvement of living conditions in today's society (CARVALHO, 2011). However, mining activities may also lead to significant environmental impacts (LONGO et al., 2011). In many cases, environmental impacts from mining activities can be mitigated by the use of appropriate environmental controls and ecological restoration techniques.

Soil is the basic substrate that supports all life on Earth (FERREIRA, 2010). The development of methods to assess soil quality is challenging (MELLONI et al., 2008) in part because the ascertainment of soil quality depends

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on the corresponding extension of its benefits to humans. Assessing soil quality is also challenging because soil quality can vary in accordance with its original composition and it is strongly linked to anthropogenic activities (ARAÚJO; KER; NEVES, 2012). Corrêa and Bento (2010) recommend that scientists study the restoration of mined ecosystems to strengthen knowledge of edaphological systems and to develop effective techniques that can improve the physical quality of substrates.

Studies focusing on the environmental recovery and restoration of high-altitude mining fields are scarce. However, the demand for new technologies that can recover landscapes in these types of phyto-physiognomies is high (BARROS et al., 2012). Therefore, the aim of this study was to characterize the physical properties of soil in high-altitude areas affected by bauxite mining operations, and to assess the responses of edaphic factors to restoration techniques used to recover mined areas in the plateau region of Poços de Caldas, Minas Gerais, Brazil.

MATERIALS AND METHODS

The study area was located in the plateau region of Poços de Caldas, Minas Gerais, Brazil (46º27'10"W e 21º54'00"S). The plateau region is located within a mountainous range area at altitudes varying between 1,000 to 1,600 m. This area encompasses the drainage networks of the Paraná River hydrographic basin, which is a sub-basin of the Rio Grande (GATTO et al., 1983). The study area has a highland subtropical, Cwb-type climate according to Köppen's climate classification system (i.e., the region is mesothermal with mild summers and dry winters). The rainy season extends from October to March, with an average annual rainfall of 1,482 mm (PREFEITURA MUNICIPAL DE POÇOS DE CALDAS-PMPC, 1992).

The region lies within the boundaries of the Atlantic Forest in South America, and it is composed of mountainous and high-mountain ombrophilous forests (VELOSO; RANGEL FILHO; LIMA, 1991) as well as gallery forests and highland fields (GUIMARÃES et al., 2008). The soil in the study area was classified according to Empresa Brasileira de Pesquisa Agropecuária-Embrapa (2006) as typical dystrophic Red Nitosol. Red Nitosol soils are red in color and are typically porous, well-structured, and acidic. The soil in the study area contained a high amount of clay and gravel and was located on strongly undulating terrain.

Open-pit mining, method usually employed by mining companies in the plateau region of Poços de Caldas, was technically developed and adapted over time, depending on the geological and topographical features of the region, as well as the market demands. The mining is carried out in the open, usually with descending advancement, which presents the best conditions for development and the ease it provides at the moment of the environmental recovery (WILLIAMS, 2001).

Once mining activity ceases, topographical reshaping is initiated via the scattering of topsoil (0-0.10 m layer, rich in organic matter and potential source of plant propagules) previously stored during the stripping of soil, followed by the subsoiling (GARDNER; BELL, 2007), sometimes crossed. Finally the definitive draining system is implantated and the revegetation of the area is done through specific technical procedures for each field reality. In the cases studied, there was no correction of pH and soil fertilization.

The quality of restored soils was assessed in this experiment by using a randomized block design. Because of uncertainty related to the homogeneity of experimental areas and to control for possible variations inherent to the mining process, the experimental design used three randomized blocks within two treatments (before the mining intervention and after environmental recovery) and four replicates were evaluated in each block.

Between January and August 2012, soil samples with deformed structures were collected at depths of 0 to 0.10 m and 0.10 to 0.20 m. These samples were assessed for granulometry and water-dispersible clay content (without added chemical dispersants) using the Bouyoucos method, and measurements of the flocculation index, particle density, stoniness (EMBRAPA, 1997). Samples were collected maintaining the soil, relatively, in their natural aggregates, to estimate the water-stable aggregates. Additional data were collected from aggregate sieving results including the percentage of aggregates retained in each sieve, the mean weighted diameter of particles, the mean geometric diameter of particles, as well information about macro- and micro-aggregates. These data were collected pursuant to the methods described in Madari et al. (2005). Organic matter content was also assessed in soil samples according to previously described methods (EMBRAPA, 2007).

Concomitantly, soil samples with preserved structures were collected at depths of 0 to 0.10 m by the volumetric ring method using an Uhland sampler. This was necessary given the large amount of gravel at greater depths throughout the soil profile. The following attributes were assessed in these samples: soil bulk density, total pore volume, macroporosity, and microporosity (EMBRAPA, 1997).

An analysis of variance (ANOVA) was used to compare treatment means for the soil parameters assessed in this study. The means of the two treatments were directly compared using an ANOVA F-test. A factorial arrangement was used for comparisons of the stoniness index values at 0-0.10 m and 0.10-0.20 m depths both before mining and after recovery.

RESULTS AND DISCUSSION

Granulometry analyses of soil samples in natural areas and in recovered areas treated after bauxite mining showed that there was no significant differences in the granulometric soil fractions across textural classes for the depths that were assessed. In all situations studied, soils belonged to the clay texture class and had clay contents ranging from 537.6 to 563.3 g kg^{-1} These data confirm that the soil profiles were texturally homogeneous.

Although soil horizon inversion is an inherent negative environmental consequence of the bauxite mining process (BARROS et al., 2012), the results obtained in this study were in accordance with those expected since the textural composition of the soil does not vary very much during its exploitation (FERREIRA, 2010). During the environmental recovery process, the first 0.10 or 0.20 m of soil are stripped prior to mining and the soil is used later in the recovery process as the primary source of nutrients, microorganisms, and propagules for regeneration of the exploited area. Importantly, Nitosols are characterized by texturally homogeneous soil profiles (EMBRAPA, 2006; GREGO; COELHO; VIEIRA, 2011).

During ANOVA analyses performed on the stoniness index values, a significant interaction was observed between the treatments and the sampling depths (0 to 0.10 m and 0.10 to 0.20 m). In the natural area (i.e., before mining intervention) the stoniness index at the 0 to 0.10 m depth (20.92%) was significantly lower than the value found at the 0.10 to 0.20 m depth (46.42%) (Figure 1). These results help to explain the difficulties encountered during sampling soils with preserved structures at depths lower than 0.10 m.

After recovery of the mined areas, stoniness index values in the different layers were not significantly different from each other, and the values were 21.50% for soils from 0 to 0.10 m in depth and 29.00% for soils from 0.10 to 0.20 m in depth. These results are probably a result of the homogenization of the soil and the remaining concretions after mining, as well as by horizon inversion and the effects on soil that are inherent to topographical reshaping. Mining operations are known to cause the restructuring of the natural organization of soil profiles (LUNARDI NETO et al., 2008).

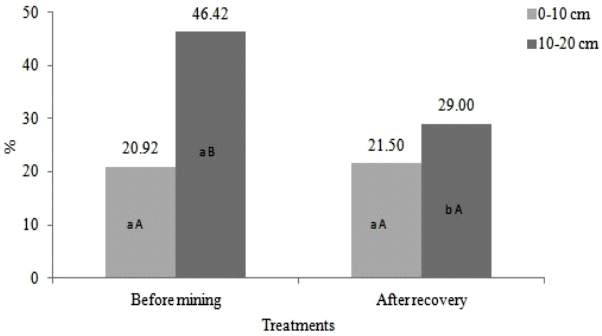

Figure 1 – Stoniness index values for soils collected at different depths before mining intervention and after the environmental recovery of bauxite deposits in the plateau region in Poços de Caldas, Minas Gerais, Brazil.
Means with the same lower case letters for treatments and the same upper case letter for depths were not statistically different from each other when they were evaluated with the F-test at a 5% significance level. Coefficient of Variation = 50.0%.

The stoniness index at the 0 to 0.10 m depth did not differ significantly between the values found in the natural area (20.92%) and in the recovering area (21.50%). In contrast, for the 0.10-0.20 m depth, the values found for the stoniness index were significantly different between treatments, which helped to confirm the existence of changes in the subsurface caused by the mining process.

Soil preparation operations during environmental recovery activities of mined areas may expose soil surfaces to rains and flooding and exacerbate erosion (PANACHUKI et al., 2011). The results of this study seem to confirm those previous findings, since we observed a lower flocculation index value in the area before mining intervention when compared to the recovering area for the two depths studied (Table 1). Further, the water-dispersible clay contents were higher in the area before mining intervention took place (Table 1).

Similar results were found by Lunardi Neto et al. (2008) and Mendes, Pereira and Melloni (2006). These authors state that decreases in the flocculation index may cause serious problems because dispersible clays can obstruct pores and reduce infiltration rates, which contribute to increased surface runoff and consequently, erosion. We expected to observe higher organic matter contents in the natural area, since the integrity of the physical, chemical, and biological components of this soil system remained intact. However, no differences in organic matter content were observed in the samples collected before mining and after recovery. It is possible that an increase in microbial activity occurred after mining, considering that the environmental modifications imposed can lead to higher flocculation indices and less water-dispersible clay contents through the exudation of ligand compounds by microorganisms (MAIO et al., 2011).

Similar to the results found in this study, Mendes, Pereira and Melloni (2006) – who studied the recovery of degraded areas in Itajubá, Minas Gerais, Brazil – observed significantly higher flocculation indices and lower water-dispersible clay contents in soils from recovery areas as compared to soils from natural areas. According to the authors, these results suggest that the areas are undergoing a soil structure recovery process, since flocculation represents the first step in the natural process of aggregate formation.

Additionally, we did not detect any significant effects of mining on particle densities at the soil depths assessed in this study, and this lack of effect was also observed by Lunardi Neto et al. (2008). The lack of effect on particle densities was likely related to the similarities in clay and organic matter contents of both soil layers under study (0-0.10 m and 0.10-0.20 m) in the natural soils and the soils recovered at the end of the mining process.

While assessing the attributes that reflect the porosity of the soil (Table 2), we observed a change in the pore distribution caused by mining activities. Therefore, there was a change in soil structure, an increase in soil density, and a decrease in the total volume of pores and macropores in soils from the recovered area in the 0-0.10 m layer. According to Arshad, Lower and Neves (1996), owing to the intrinsic dynamics of soil density and porosity arising from its use, those parameters are reflective of soil quality and directly influence the behavior of root development in plants and the degree of soil compaction.

Decreases in the number of soil micropores can occur because of the kinetic energy of raindrops, deep tillage, micropore obstruction, the mechanical pressure of agricultural machinery, and a reduction in organic matter and nutrient content (ARAÚJO; KER; NEVES, 2012).

Table 1 – Physical soil properties and organic matter contents of soils collected at different depths before mining intervention and after the environmental recovery of bauxite deposits in the plateau region in Poços de Caldas, Minas Gerais, Brazil.

Treatments	Water-Dispersible Clay	Flocculation Index	Particle Density	Organic Matter
	---------------------- % ----------------------		kg dm^{-3}	g kg^{-1}
		0-0.10 m		
Before mining	42.09 a	24.77 b	2.40 a	36.50 a
After recovery	36.82 b	34.52 a	2.41 a	32.80 a
CV (%)	11.00	27.00	3.00	28.00
		0.10-0.20 m		
Before mining	40.55 a	23.88 b	2.40 a	28.60 a
After recovery	34.50 b	38.60 a	2.41 a	28.80 a
CV (%)	16.00	39.00	2.00	27.00

* Means followed by the same letter in the column do not differ statistically according to results from the F-test at a 5% significance level. CV: Coefficient of Variation.

Table 2 – Bulk density and porosity of soils collected at a depth of 0-0.10 m before mining intervention and after the environmental recovery of bauxite deposits in the plateau region in Poços de Caldas, Minas Gerais, Brazil.

Treatments	Soil bulk Density	Total Pore Volume	Micropores	Macropores
	kg dm^{-3}	-------------------------------- % --------------------------------		
Before mining	1.12 b	53.25 a	29.01 a	24.24 a
After recovery	1.33 a	45.16 b	28.78 a	16.38 b
CV (%)	14.00	14.00	16.00	39.00

* Means followed by the same letter in the column do not differ statistically according to results from the F-test at a 5% significance level. CV: Coefficient of Variation.

There were, however, no significant differences in microporosity observed between the soils assessed in this study (Table 2). Aratani et al. (2009) found similar results that depended upon the degree of soil mechanization for different types of soil management in the state of São Paulo. Our results obtained through the analyses of soil samples with non-deformed structures may deviate slightly from values for other soils in the region due the high concretion content already previously discussed. Gonçalves et al. (2011) – who worked with dystroferric Red Nitosol (Alfisol) soils in the state of Paraná, Brazil – found soil density values ranging from 0.90 to 1.38 kg dm^{-3}.

Within the context of this study, changes in soil structure may facilitate the establishment of exotic species and suppress the presence of more sensitive native species, which could result in changes to the floral structure of the fields. Hence, the occurrence of exotic species at restoration sites should be monitored as they represent an ecological hazard, especially in regards to the environmental recovery processes (SOCIETY FOR ECOLOGIAL RESTORATION-SER, 2004).

Decreases in macroporosity and total pore volume of the soil correspond to less space being available for adequate soil aeration and oxygen diffusion from the soil to plants. Therefore, given the same moisture content, aeration porosity will likely be lower in recovered soils when compared to that found in natural areas.

Soil aggregation was assessed by the stability of soil aggregates in water. We observed lower particle diameter values in soils after recovery activities in mined areas for the two depths under study (Table 3). These data demonstrate the sensitivity of using soil aggregate indicators to detect physical changes in the soil arising from mining activity. It is noteworthy that even the lowest mean particle diameter observed in this study (4.78 mm at 0-0.10 m in depth in recovered soils) was bigger than the 4.30 mm mean geometric particle diameter (MGD) that was found in sub-savannah oxidic Latosol (Oxisol) areas from similar soil depths by Oliveira et al. (2004). Hence, our results suggest that there was good structuring of the Nitosols, which were able to maintain good soil quality indicator levels even after intense mining activity.

According to Madari et al. (2005), soils with high structural stability show good aggregation. The highest aggregate concentrations in this study occurred in the particle size classes that were larger than 2.00 mm (Table 3), and soils from the area before mining had significantly higher values for such aggregates. However, for the other size classes the highest aggregate percentages were generally found in recovery areas. This was true for all treatments except for particle size classes smaller than 0.105 mm where no significant differences were found.

Reductions in soil aggregation were likely a consequence of topographical reshaping activities and other mechanical practices used in the environmental recovery process. These activities can cause the destruction of larger

Table 3 – Mean geometric diameter (MGD), mean weighted diameter (MWD), and size distribution of soil aggregates collected at different depths before mining intervention and after the environmental recovery of bauxite deposits in the plateau region in Poços de Caldas, Minas Gerais, Brazil.

Treatments	MGD	MWD	Aggregate sizes (mm)						Ma	Mi
			8.0-2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.105	< 0.105		
	------ mm ------		------ % ------							
0-0.10 m										
Before mining	4.90 a	4.96 a	99.0 a	0.4 b	0.3 b	0.1 b	0.1 b	0.1 b	99.8 a	0.2 b
After recovery	4.78 b	4.91 b	96.8 b	1.4 a	0.9 a	0.4 a	0.2 a	0.3 a	99.5 b	0.5 a
CV (%)	4.00	2.00							0.10	57.00
0.10-0.20 m										
Before mining	4.91 a	4.96 a	99.1 a	0.5 b	0.1 b	0.1 b	0.1 b	0.1 a	99.8 a	0.2 a
After recovery	4.79 b	4.91 b	97.7 b	1.0 a	0.7 a	0.3 a	0.2 a	0.1 a	99.7 a	0.3 a
CV (%)	2.00	1.00							0.20	66.00

* Means followed by the same letter in the column do not differ statistically according to results from the F-test at a 5% significance level. Ma: Macroaggregates; Mi: Microaggregates. CV: Coefficient of Variation.

soil aggregates. Similar results were found by Garbiate et al. (2011) and they concluded that more intensive practices created lower mean particle diameter values, which are indicative of soil aggregate destruction.

By analyzing the distribution of macro- and microaggregates in soil samples, it was possible to see that macroaggregates were the predominant form in both soil layers (Table 3). There was a statistically significant reduction in macroaggregates in the 0-0.10 m layer after mining intervention. For the 0.10-0.20 m layer, the trend was not significant. Although no significant changes in organic matter content occurred after mining activities for both layers under study, there was an increase in the particle flocculation indices, which suggests that the soil is still in the process of recovery and structural reshaping. Considering that changes occurred in natural conditions as a consequence of the physical and chemical changes to the mined area, it is believed that these changes may also affect biological processes associated with soil aggregation (Moreira; Siqueira, 2006).

CONCLUSIONS

Following the recovery of soils in the mined area, there was a homogenization of stoniness between soil layers as a consequence of soil mobilization. These changes were verified by a reduction in stoniness in the 0.10-0.20 m soil layer.

Environmental recovery practices and processes in the studied mined area maintained organic matter levels, increased the degree of soil flocculation, and reduced water-dispersible clay content.

Mining activities caused structural changes in the superficial layer of the soil, which was evidenced by increases in soil density and decreases in the total porosity and macroporosity of the soil.

There was a reduction in water aggregate stability after mining, although indicator levels were still reasonably good and likely attributable to the recovery process.

In summary, physical properties of the soil affected by the mining process did not show excessive variations. Hence, we recommend a reduction in the number of passes of machinery and equipment over the soil, which would help to optimize operations performed during preparation of the area. Additionally, other studies should be conducted on the behavior of these environments in the presence of mining activities. These studies would be valuable for consolidating the scientific knowledge needed to replicate environmental restoration techniques in areas degraded by mining activities. Lastly, we recommend that the amount of topsoil obtained during strip mining be increased for the maintenance of soil organic matter levels.

ACKNOWLEDGEMENTS

The authors thank the Brazilian Aluminum Company for intellectual and logistical support and for granting access to the study area. The authors also thank the Forest Science Department for its technical and scientific support and FAPEMIG for its scientific support. We are grateful to professors Julio Silvio de Sousa Bueno Filho, João José Granate de Sá e Melo Marques, administrative technicians Dulce and Doroteo, and the field assistant José Fernandes for their assistance with this research. This study was funded by a grant from CAPES.

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