



Assisted natural regeneration as a technique for restoring an area after bauxite mining, Minas Gerais, Southeast Brazil

Regeneração natural assistida como técnica para a restauração de uma área após mineração de bauxita, Minas Gerais, Sudeste do Brasil

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ABSTRACT

The objective of this study was to evaluate the floristic composition, phytosociological parameters, and soil chemical attributes to assess the efficiency of assisted natural regeneration, based on topsoil transfer, for forest restoration six years after bauxite mining. The forest inventory included all individuals with a Circumference at Breast Height (CBH) ≥ 10 cm, and phytosociological parameters were analyzed using Fitopac 2.1 software. The area was dominated by early successional species (pioneers and early secondary). The study revealed a low floristic diversity ($H' = 1.374$) and equitability ($J' = 0.48$), with dominance of the genus *Vernonanthura*. Assisted natural regeneration proved efficient in providing soil coverage and contributed to the recovery of soil attributes such as organic matter, soil pH, sum of bases, cation exchange capacity, total-N, and increased levels of K, Ca, Mg, Mn, and Zn. To enhance floristic diversity and accelerate the restoration process, we recommend controlling invasive grasses, enriching the area with native tree species from later successional stages, and applying nucleation techniques.

Keywords: Atlantic Forest; Ecological restoration; Soil chemical attributes; Sustainability; Topsoil transfer.

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RESUMO

*O objetivo deste estudo foi avaliar a composição florística, os parâmetros fitossociológicos e os atributos químicos do solo para analisar a eficiência da regeneração natural assistida, baseada na transferência de solo superficial, para a restauração florestal seis anos após a mineração de bauxita. O inventário florestal incluiu todos os indivíduos com Circunferência à Altura do Peito (CAP) ≥ 10 cm, e os parâmetros fitossociológicos foram analisados utilizando o software Fitopac 2.1. A área apresentou predominância de espécies de sucessão inicial (pioneiras e secundárias iniciais). O estudo revelou baixa diversidade florística ($H' = 1,374$) e equabilidade ($J' = 0,48$), com domínio do gênero *Vernonanthura*. A regeneração natural assistida mostrou-se eficiente na cobertura do solo e contribuiu para a recuperação de atributos do solo, como matéria orgânica, pH, soma de bases, capacidade de troca catiônica, nitrogênio total, e aumento nos níveis de K, Ca, Mg, Mn e Zn. Para aumentar a diversidade florística e acelerar o processo de restauração, recomenda-se controlar gramíneas invasoras, enriquecer a área com mudas de espécies nativas de estágios de sucessão mais avançados e aplicar técnicas de nucleação.*

Palavras-chave: Mata Atlântica; Restauração ecológica; Atributos químicos do solo; Sustentabilidade, Transposição de topsoil.

1. INTRODUCTION

Brazil is the fourth largest producer of bauxite, accounting for approximately 7.8% of the world's production, and it also holds the fourth largest bauxite reserve globally (USGS, 2024). The bauxite exploitation generates an important source of income for Brazil through the generation of jobs (direct and indirect), regional development and export of the produced materials (ANM, 2025). In the Brazilian scenario, the state of Minas Gerais stands out as the second largest bauxite-producing state (ANM, 2025). However, bauxite mining causes impacts due to the removal of vegetation cover and changes in soil properties (BARBOSA *et al.*, 2022; CAVALCANTE *et al.*, 2023). Taken into account the scale and impact of the exploitation process, bauxite mining can be considered "less invasive" compared to other types of mining (e.g., clay, gold, iron mining), as it does not involve larger territorial areas and primarily requires the removal of the topsoil (surface and fertile layer) (KAMBLE; BHOSALE, 2019; MARTINS *et al.*, 2020).

In this context, demands for forest restoration in bauxite mining areas are considered a global priority for the mineral exploration process to occur in a sustainable manner (BALESTRIN *et al.*, 2020; MARTINS *et al.*, 2020; COSIMO *et al.*, 2021; FONSECA *et al.*, 2024a). There are active restoration methods involving direct human intervention, such as planting seedlings, nucleation techniques, green manure, as well as passive restoration methods like natural regeneration (NETO *et al.*, 2021; MARTINS *et al.*, 2022; OLIVEIRA *et al.*, 2022; FONSECA *et al.*, 2023; ROCHA *et al.*, 2023; FONSECA *et al.*, 2024a). In this sense, the choice of efficient techniques of restoration performs an important role in support to make a "stable" condition until that the nature becomes able to follow this process by itself, that is, without external interventions (LEI *et al.*, 2016; MARTINS, 2018; COSIMO *et al.*, 2021).

Natural regeneration is a gradual process of secondary succession that involves ecological processes of species colonization, adaptation, and community assembly (CHAZDON; GUARIGUATA, 2016; FONSECA *et al.*, 2017). When supported by specific techniques, such as controlling invasive grasses, protecting against fire and grazing, enrichment planting, nucleation practices, or topsoil transposition, it can be framed as assisted natural regeneration (ANR), which enhances natural



resilience and accelerates the recovery of ecological functions (OLUWAJUWON *et al.*, 2024; RAJAPAKSHE *et al.*, 2024). ANR represents a simple and cost-effective approach for restoring disturbed areas, as it allows the environment to reestablish ecological interactions and provide ecosystem services (YANG *et al.*, 2018; CHAZDON *et al.*, 2017; LATAWIEC *et al.*, 2016; STRASSBURG *et al.*, 2016; WILSON *et al.*, 2022). Recent studies highlight that ecological restoration in tropical forests can be more successful with natural regeneration, whether spontaneous or assisted, than with active restoration through planting (CROUZEILLES *et al.*, 2017; ROZENDAAL *et al.*, 2019; CHAZDON *et al.*, 2023).

In this perspective, evaluating the floristic composition and structure of tree communities is essential to understand the natural dynamics of the area (SUGANUMA; DURIGAN, 2015), identify ecological barriers such as the absence of certain species or functional groups (SUGANUMA *et al.*, 2014), reduce the time and resources required for effective restoration (REIJ; GARRITY, 2016), detect development patterns (CROUZEILLES *et al.*, 2017), and identify agents that negatively affect the restoration process, thereby supporting measures to mitigate their impacts (BALESTRIN *et al.*, 2019a; FONSECA *et al.*, 2024b).

The hypothesis of this study is that assisted natural regeneration through topsoil transposition after bauxite mining in the Atlantic Forest can increase plant cover, but is insufficient to fully restore high species diversity. Therefore, we evaluated the floristic composition, phytosociological parameters, and soil chemical attributes to assess the effectiveness of assisted natural regeneration for forest restoration six years after bauxite mining in Southeastern Brazil.

2. MATERIAL AND METHODS

2.1. Study area

The study was conducted in the municipality of São Sebastião da Vargem Alegre, southeastern Minas Gerais State, Brazil (21°01'58.82" S and 42°34'59.82" W), in a 0.5-hectare area under assisted natural regeneration after bauxite exploitation by Companhia Brasileira de Alumínio (CBA) (Figure 1).

Figure 1 – Location of the study area (highlighted), in São Sebastião da Vargem Alegre, Minas Gerais State, Brazil.



Source: authors.



The climatic classification for this region is type Cwb, high-altitude subtropical climate, with mild, rainy summers and dry winters. In addition, the annual average rainfall from 750 mm to 1,800 mm, with the rainy season from November to April and the dry season from May to October (ALVARES *et al.*, 2013). The natural vegetation in the region is classified as Semi-Deciduous Seasonal Forest and is under the biome Atlantic Rain Forest (IBGE, 2012). The soils are classified as Yellow-Red Latosol (SANTOS *et al.*, 2018), which corresponds to an Oxisol (Soil Survey Staff, 2022) and Ferralsols (IUSS Working Group WRB 2022). The region has elevations ranging from 217 to 1355 m (USGS, 2000). The study area is an experimental site under assisted natural regeneration following bauxite mining. The surroundings include native forest patches, pastures, agricultural fields, and areas at different stages of ecological recovery. Adjacent land uses comprise monocultures of *Eucalyptus*, monocultures of *Anadenanthera peregrina*, and mixed plantings of 16 native Atlantic Forest species arranged in a quincunx pattern.

Prior to bauxite exploitation in 2009/2010, the area had been used for agriculture, specifically coffee cultivation for about 10 years, and historically for livestock grazing (pasture). During preparation for mining, the superficial soil layer (0 – 0.2 m) was removed and stored near the site for approximately one year. After mining, the area underwent topographic reconfiguration, deep subsoiling to a depth of 0.60 m to reduce compaction, and fertilization. The previously stored topsoil was then reapplied to cover the mined area, favoring assisted natural regeneration. Six years after bauxite exploitation, the floristic composition and structure of the vegetation were assessed.

2.2. Floristic evaluation

The forest inventory of all tree individuals with circumference at breast height (CBH) ≥ 10 cm was carried out and then calculated the phytosociological parameters (density and dominance relative, coverage value) and diversity index of the vegetal community (Shannon-Wiener and equability). All the individuals were classified in families and scientific nomenclature according to Angiosperm Phylogeny Group (APG IV, 2016). The species names were confirmed using the Flora e Funga do Brasil 2023 (<http://floradobrasil.jbrj.gov.br>).

Furthermore, the species found were classified in successional categories according to Gandolfi *et al.* (1995) for Brazilian secondary forests in: pioneers (P); early secondary (ES); late secondary (LS) and non-classified (NC). Considering the dispersal syndrome, the species were classified, according to Van der Pijl (1982) in: dispersal by animals (ZOO); dispersal by wind (ANE); self-dispersal (AUT) and non-classified (NC).

Moreover, the phytosociological parameters of the community were calculated for the species and botanical families found in the study area.

2.3. Soil analysis

The soil chemical and physical analysis in the study area was performed by obtaining thirty soil sample points, randomly collected in the whole area of interest. By the fact that the topographic reconstruction and consequently used the topsoil previously taken from the area, the soil samples reflected the soil characteristics of this superficial layer, and by this reason, the thirty samples obtained were mixed and generated only one composite sample.



Thus, the sampling was carried out using soil auger to a depth of 0 to 20 cm. The composite sample was sent to the Soil Laboratory of the Universidade Federal de Viçosa to analyze the chemical characteristics. Subsequently, the results were interpreted according to the Recommendation Guide for correctives and fertilizers of Minas Gerais (RIBEIRO *et al.*, 1999).

2.4. Processing and data collection

In order to analyze the phytosociological data, the software FITOPAC 2.1 was applied to evaluate the horizontal structure through density and dominance parameters (SHEPHERD, 2010). In addition, we calculated the coverage value, Shannon diversity index (H') and equability index (J'). The graphs were created using R software (version 4.4.1; R Core Team, 2024) with the 'geom_bar' function, available in the 'ggplot2' package (Wickham, 2016).

3. RESULTS AND DISCUSSION

3.1. Floristic composition and species diversity

In the floristic survey, 541 individuals, including 18 species and 11 botanical families were found (Table 1). The results demonstrate clearly the vegetal characteristics of this area (young community in process of development), with dominant presence of the pioneer and early secondary species. The density of the individuals in the study area was 1082 individuals per hectare, with a Shannon-Wiener index (H') = 1.37, evidencing a low floristic diversity in this area. The equability which was calculated through the Pielou evenness index (J'), was 0.48, evidencing also a low diversity and floristic abundance in the community.

Table 1 – Floristic list of the species found in the study area after the bauxite exploitation.

Botanical Family / Specie	Successional Category	Dispersal Syndrome
Asteraceae		
<i>Baccharis dracunculifolia</i> DC.	P	Ane
<i>Piptocarpha macropoda</i> (DC.) Baker	P	Zoo
<i>Symphypappus itatiayensis</i> (Hieron.) R.M.King <i>et</i> H.Rob.	P	Ane
<i>Vernonanthura diffusa</i> (Less.) H.Rob.	P	Ane
<i>Vernonanthura discolor</i> (Spreng.) H.Rob.	P	Ane
<i>Vernonanthura phosphorica</i> (Vell.) H.Rob.	P	Ane
Bignoniaceae		
<i>Jacaranda micrantha</i> Cham.	P	Ane
<i>Sparattosperma leucanthum</i> (Vell.) K.Schum.	ES	Ane
Cannabaceae		
<i>Trema micrantha</i> (L.) Blum.	P	Zoo
Fabaceae		
<i>Piptadenia gonoacantha</i> J.F. Macbr.	ES	Aut
<i>Senna multijuga</i> (Rich.) H.S. Irwin <i>et</i> Barneby	ES	Aut
Indeterminate		
Indeterminate	NC	NC
Melastomataceae		
<i>Tibouchina granulosa</i> (Desr.) Cogn.	P	Zoo
Myrtaceae		
<i>Psidium guajava</i> L.	P	Zoo



Primulaceae		
<i>Myrsine ferruginea</i> (Ruiz et Pav.) Spreng.	ES	Zoo
Rutaceae		
<i>Dictyoloma vandellianum</i> A. Juss.	ES	Ane
Solanaceae		
<i>Solanum mauritianum</i> Scop.	P	Zoo
Verbenaceae		
<i>Lantana camara</i> L.	P	Zoo

Where: Successional Category: (P = Pioneer, ES = Early Secondary); Dispersal Syndrome: (Ane = Anemochoric, Aut = Autochoric, Zoo = Zoochoric), and NC = non-classified.

Source: authors.

In addition, low floristic diversity was observed in this area, as well as floristic dominance of the Asteraceae family, which was also verified by Ataíde *et al.* (2011) in an area of ferruginous field of Quadrilátero Ferrífero - MG. The Pielou evenness index ($J' = 0.48$) indicates a moderately homogeneous distribution of individuals among species, reflecting an intermediate pattern between uniformity and strong dominance, largely explained by the prevalence of the genus *Vernonanthura* (CV = 65.9 %). Other studies performed in different areas, successional stages and different time intervals after the mining process that present similar results (low diversity), were verified by Araújo *et al.* (2006), Corrêa and Melo-Filho (2007), Lima *et al.* (2018) and Neto *et al.* (2021). According to the results, 33.3 % of all the species found in the study area belong to the Asteraceae family, demonstrating the largest floristic richness from this family in the community. Other families that presented a good representability in the area were Fabaceae and Bignoniaceae (floristic richness of 11.1 % each one), while the other ones were composed by only one individual in each family (5.5 % each one).

The landscape characteristics such as connectivity, range of the impacts produced, techniques used, biome, among others, can directly influence the floristic composition and, consequently, the restoration process (VILLA *et al.*, 2021; FONSECA *et al.*, 2024a). It can be observed in studies performed by Araújo *et al.* (2006) and Corrêa and Melo-Filho (2007) in areas with approximately 20 years of natural regeneration, where a great variation in the number of species was observed (from 5 to 47), which corroborates with the idea that each environment should be analyzed individually. Moreover, the low floristic diversity verified in mined environments can also be observed in areas of natural regeneration. It was verified by Klein *et al.* (2009) and Guimarães (2015) in areas post coal mining (28 years later) and areas with different successional stages post bauxite mining in Poços de Caldas - MG, respectively.

However, we must be careful when comparing different situations and areas in process of restoration because the characteristics around the area (landscape); pressure suffered (natural either anthropic); distance from propagules sources; fauna; diversity; edaphic conditions; among others), are different in each situation, area or region and it can influence with different intensity on each place (BALESTRIN *et al.*, 2019b). Thus, a factor that may have influenced the results of the current study regarding low diversity was the "isolation" of the area undergoing restoration, as it is surrounded by eucalyptus plantations and coffee cultivation (experimental fields around). In addition, the invasion by *Urochloa decumbens* Stapf and *Urochloa plantaginea* (Link) Hitchc. (invasive grasses) can have impaired the successional advance and, consequently, the increase of vegetal diversity in the study area (MARTINS *et al.*, 2021).



The importance of this question was observed by Suganuma *et al.* (2014), which affirms that the distance from propagules sources can create obstacles to ecological restoration. In this same sense, Chazdon and Guariguata (2016), Aavik and Helm (2018) and Cosimo *et al.* (2021) observed that the landscape quality and the connectivity between the areas (natural and those areas in process of restoration), contribute to improve the resilience and restore the ecological functions of the degraded areas.

Thus, the control of invasive grasses (*U. decumbens* and *U. plantaginea*) is recommended for the study area. Moreover, in order to improve the diversity in the area, we recommend enrichment with native species in more advanced stages of succession (late secondary and climax species). Additionally, another suggestion is the use of native species that have attractiveness for the local fauna, in order to improve the flow and interactions between the environmental elements from the region.

3.2. Functional groups and phytosociological parameters

Regarding the distribution of the species into successional categories, the pioneer species showed dominance over the early secondary species (66.6 % and 27.7 % respectively). According to the dispersal syndrome, most of the species in the study area presented dispersal by wind (50 %), followed by the dispersal by animals (38.9 %).

In addition, the families that presented the largest coverage values (CV) in the community were: Asteraceae, Cannabaceae and Fabaceae, representing the percentage of 45 %, 17.54 % and 10.84 % respectively (Table 2). It demonstrates the importance and dominance of these families in the plant community, which together sum 95.83 % of the whole community.

Table 2 – Phytosociological parameters of the botanical families found in the study area.

Botanical family	Nº ind.	Nº species	Rel. De. (%)	Rel. Do. (%)	CV (%)
Asteraceae	436	6	80.59	54.31	67.45
Cannabaceae	34	1	6.28	28.81	17.54
Fabaceae	46	2	8.50	13.18	10.84
Melastomataceae	16	1	2.96	2.31	2.63
Verbenaceae	2	1	0.37	0.34	0.35
Bignoniaceae	2	2	0.37	0.13	0.25
Solanaceae	1	1	0.18	0.52	0.35
Indeterminate	1	1	0.18	0.29	0.24
Rutaceae	1	1	0.18	0.04	0.11
Primulaceae	1	1	0.18	0.04	0.11
Myrtaceae	1	1	0.18	0.04	0.11
Total	541	18	100	100	100

Where: Nº ind: Number of the individuals; Nº species: Number of the species; Rel.De.: Relative density; Rel.Do.: Relative dominance; CV%: Coverage value.

Source: authors.

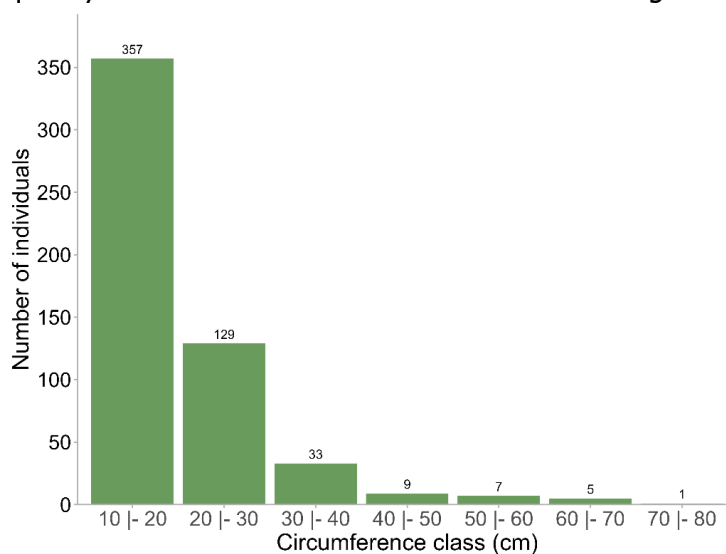
In the Asteraceae family, it was observed that the species *Vernonanthura phosphorica* (Vell.) H.Rob. and *Vernonanthura diffusa* (Less.) H.Rob. presented a coverage value of 45.88 % and 20.05 %, respectively. Another species that had a good coverage value was the *Trema micrantha* (L.) Blum.



of the Cannabaceae family, with coverage value of 17.54 %. Thus, together these three species presented a total coverage value of 83.4 %.

Regarding the distribution of the vegetal community across diameter classes, the area exhibited an "inverted J" pattern, largely driven by the high concentration of small-diameter individuals, particularly from the genus *Vernonanthura* (65.99 % in the first diameter class), with a gradual decrease towards larger classes (Figure 2).

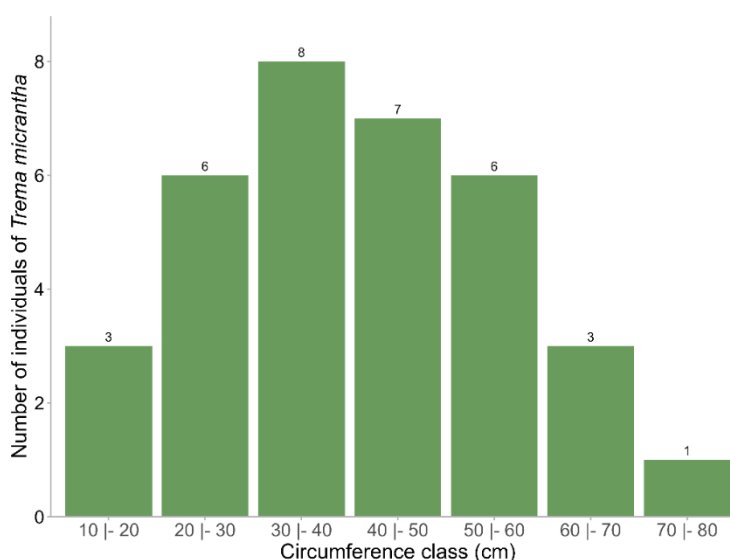
Figure 2 – Frequency distribution of individuals in the natural regeneration study area.



Source: authors.

In contrast, the species *T. micrantha* displayed a different diameter distribution pattern compared to that of the overall vegetal community. Most individuals were concentrated in intermediate diameter classes, resulting in a distribution resembling a normal curve. This pattern likely reflects the typical rapid growth strategy of this species.

Figure 3 – Frequency distribution of *Trema micrantha* in the natural regeneration study area.



Source: authors.



3.3. Soil attributes

In the face of soil characteristics verified in the soil samples collected, levels of the clay higher or equal to 35 % were observed. Regarding the chemical characteristics in the current situation (in process of restoration), a good level of the acidification was observed ($\text{pH-H}_2\text{O} = 5.77$), intermediate levels of the Organic Matter ($\text{OM} = 3.86$), Base sum ($\text{BS} = 2.33$) and effective Cation Exchange Capacity ($\text{CEC} = 2.33$). On the other hand, the Basis Saturation index presented low levels ($V = 23.5$) in the collected soil samples. Thus, in order to evaluate, relate and compare the soil chemical characteristics in different situations: native forest (NAT); after the topographic reconstruction (P_MIN) and current situation in process of restoration (P_RES), Table 3 was elaborate. The data from the native forest and after the topographic reconstruction were taken from study by Borges (2013), which was also performed in the study area.

Table 3 - Variation of the soil chemical characteristics in the study area.

Chemical analysis															
Sample (0-20cm)	Total-N (dag/kg)	pH (H ₂ O)	P (mg/dm ³)	K ⁺	Ca ²⁺	Mg ²⁺	H+Al (cmolc/dm ³)	BS	CEC	V %	OM (dag/kg)	Cu	Mn	Fe	Zn
															11.
NAT*	0.340	4.68	1.92	58.65	0.20	0.02	14.03	0.37	1.79	2.60	9.20	0.30	0.02	262.77	09
															1.2
P_MIN*	0.085	5.23	1.05	27.37	0.37	0.13	3.91	0.57	0.67	12.72	2.50	0.60	5.04	174.91	5
															17.
P_RES	0.130	5.77	0.80	124.00	1.34	0.67	7.60	2.33	2.33	23.50	3.86	0.36	6.90	98.10	35

Where: NAT = Soil samples collected in the surrounding native forest area (reference environment); P_MIN = Soil samples collected after the mineral exploitation and topographic reconstruction; P_RES = Soil samples collected after 6 years of natural regeneration.

Source: Borges (2013)* and compiled by the authors.

Comparing the soil samples collected immediately after bauxite mining (P_MIN*) with the soil samples collected after 6 years of natural regeneration (P_RES), we can observe a significant increase in certain soil chemical parameters (Total-N, soil pH, CEC, BS, V, OM) and an increase in nutrient levels: K, Ca, Mg, Mn, and Zn. This highlights the positive effect of assisted natural regeneration in enhancing soil fertility. Furthermore, it was observed that some soil chemical parameters in P_RES are higher than those observed in the native forest (NAT*) before bauxite mining activities, such as soil pH, t, BS, V, and the elements K, Mg, Cu, Mn, and Zn. In this sense, the improvement in certain soil chemical parameters can be explained by the fertilization and other techniques employed by the company for soil and water conservation after bauxite mining, resulting in an enhancement of the fertility levels in this area (BORGES *et al.*, 2019; BIZUTI *et al.*, 2020; CAVALCANTE *et al.*, 2023; FONSECA *et al.*, 2023).

According to a study realized by Xiao *et al.* (2016), the potential of hydrogen (pH), total organic carbon, which is derived from organic matter, total-nitrogen and available phosphorus are the main elements that affect the functional diversity of the soil. In addition, Spain *et al.* (2018), present that the higher concentrations of nitrogen and phosphorus found in soil from native forests before the



mining process can be related to higher levels of organic matter in these sites. This can be explained by the greater development and diversity of established vegetation and by the complex interactions that exist (MACHADO *et al.*, 2019; COVERDALE; DAVIES, 2023; WU *et al.*, 2024; YANG *et al.*, 2024).

Monitoring edaphic parameters is important in forest restoration of post-bauxite mining areas as it allows for the assessment of soil fertility recovery and the evaluation of the effectiveness of restoration techniques used (BORGES *et al.*, 2019; CAVALCANTE *et al.*, 2023; FONSECA *et al.*, 2023). Through this monitoring, we can observe that, although there is a decrease in the content of some elements immediately after the mineral extraction process, with the advancement of the successional process and the application of appropriate management techniques, a gradual improvement in soil quality can be observed, contributing to ecological restoration and the sustainability of the area. VALOIS-CUESTA; MARTINEZ-RUIZ, 2016).

In this sense, we can state that, in some cases, assisted natural regeneration can be successfully applied following bauxite mining, as also reported by Miranda-Neto *et al.* (2014) and Silva *et al.* (2020). This approach supports the re-establishment of vegetation, contributes to increased plant cover, enhances species diversity, and helps restore ecological functions, thereby improving the environmental sustainability of the area (CHAZDON *et al.*, 2023; OLUWAJUWON *et al.*, 2025).

The findings also emphasize the fundamental role of topsoil transposition in the restoration of bauxite-mined areas (ONÉSIMO *et al.*, 2021; FIGUEIREDO *et al.*, 2024). By reapplying the previously removed and stored soil, it was possible to accelerate the establishment of vegetation and to improve key soil fertility attributes (SOUZA *et al.*, 2025). This practice favors the germination of seeds and the resprouting of vegetative propagules contained in the soil seed bank, thereby enhancing the effectiveness of assisted natural regeneration (MARTINS *et al.*, 2021). Nevertheless, although the recovery of soil properties and vegetation cover was satisfactory, the low species diversity observed indicates the need for complementary measures (FONSECA *et al.*, 2024a). Long-term monitoring is therefore crucial to verify whether the restoration trajectory progresses toward higher species richness, greater structural complexity, and more stable ecosystem functions (CHAZDON *et al.*, 2023).

4. CONCLUSIONS

Assisted natural regeneration proved effective in the establishment of tree and shrub vegetation six years after bauxite mining, with topsoil transposition playing a key role in this process. The area exhibited low floristic diversity, with strong dominance of pioneer species, particularly from the genus *Vernonanthura* (Asteraceae), which largely contributed to soil coverage.

Furthermore, the regenerating vegetation positively influenced soil properties, enhancing organic matter, soil pH, sum of bases, cation exchange capacity, total N, and levels of K, Ca, Mg, Mn, and Zn.

While passive forest restoration through assisted natural regeneration can provide satisfactory soil coverage in bauxite-mined areas, additional measures are necessary to increase species diversity. To improve the restoration trajectory, it is recommended to control invasive grasses, enrich the area through the planting of seedlings — preferably in nuclei — and apply nucleation techniques.



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