Revista Thema
v.24 | n.2 | 2025
p.1-16

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

CIÊNCIAS AGRÁRIAS

# 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*

Diego Balestrin[1]
http://lattes.cnpq.br/7760744281726016 https://orcid.org/0000-0002-4639-4231

Sebastião Venâncio Martins[2]
http://lattes.cnpq.br/4506693662190287 https://orcid.org/0000-0002-4695-987X

Wesley da Silva Fonseca[3]
http://lattes.cnpq.br/8420490747128260 https://orcid.org/0000-0001-5197-4989

## 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.

[1] Universidade Federal de Viçosa (UFV), Departamento de Engenharia Florestal, Laboratório de Restauração Florestal (LARF), Viçosa, Minas Gerais, Brazil. E-mail: diego.balest@gmail.com

[2] Universidade Federal de Viçosa (UFV), Departamento de Engenharia Florestal, Laboratório de Restauração Florestal (LARF), Viçosa, Minas Gerais, Brazill. E-mail: venancio@ufv.br

[3] Universidade Federal de Viçosa (UFV), Departamento de Engenharia Florestal, Laboratório de Restauração Florestal (LARF), Viçosa, Minas Gerais, Brazil. E-mail: wesley.fonseca@ufv.br

Revista Thema
v.24 | n.2 | 2025
p.1-16
DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

*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

Revista Thema
v.24 | n.2 | 2025
p.1-16
DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

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 (21º01'58.82" S and 42º34'59.82" 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.

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

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.

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

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 | | |
| *Baccharis dracunculifolia* DC. | P | Ane |
| *Piptocarpha macropoda* (DC.) Baker | P | Zoo |
| *Symphyopappus itatiayensis* (Hieron.) R.M.King *et* H.Rob. | P | Ane |
| *Vernonanthura diffusa* (Less.) H.Rob. | P | Ane |
| *Vernonanthura discolor* (Spreng.) H.Rob. | P | Ane |
| *Vernonanthura phosphorica* (Vell.) H.Rob. | P | Ane |
| Bignoniaceae | | |
| *Jacaranda micrantha* Cham. | P | Ane |
| *Sparattosperma leucanthum* (Vell.) K.Schum. | ES | Ane |
| Cannabaceae | | |
| *Trema micrantha* (L.) Blum. | P | Zoo |
| Fabaceae | | |
| *Piptadenia gonoacantha* J.F. Macbr. | ES | Aut |
| *Senna multijuga* (Rich.) H.S. Irwin *et* Barneby | ES | Aut |
| Indeterminate | | |
| Indeterminate | NC | NC |
| Melastomataceae | | |
| *Tibouchina granulosa* (Desr.) Cogn. | P | Zoo |
| Myrtaceae | | |
| *Psidium guajava* L. | P | Zoo |

Revista Thema
v.24 | n.2 | 2025
p.1-16
DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

| | | |
|---|---|---|
| Primulaceae | | |
| *Myrsine ferruginea* (Ruiz *et* Pav.) Spreng. | ES | Zoo |
| Rutaceae | | |
| *Dictyoloma vandellianum* A. Juss. | ES | Ane |
| Solanaceae | | |
| *Solanum mauritianum* Scop. | P | Zoo |
| Verbenaceae | | |
| *Lantana camara* 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 Ataide *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).

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

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 | N° 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.

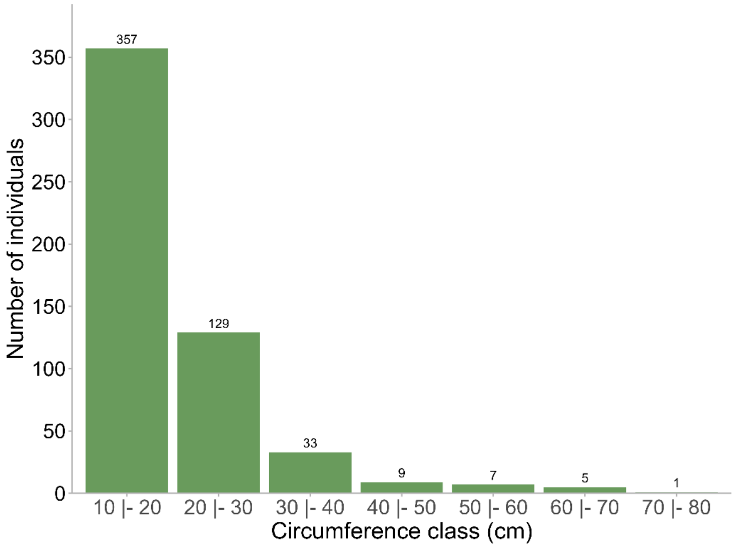
In the Asteraceae family, it was observed that the species *Vernonanthura phosphorica* (Vell.) H.Rob. and *Vernonanthura diffusa* (Less.) H.Rob. presented a coverage value of 45.88 % and 20.05 %, respectively. Another species that had a good coverage value was the *Trema micrantha* (L.) Blum.

Revista Thema
v.24 n.2 2025
p.1-16
DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

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).

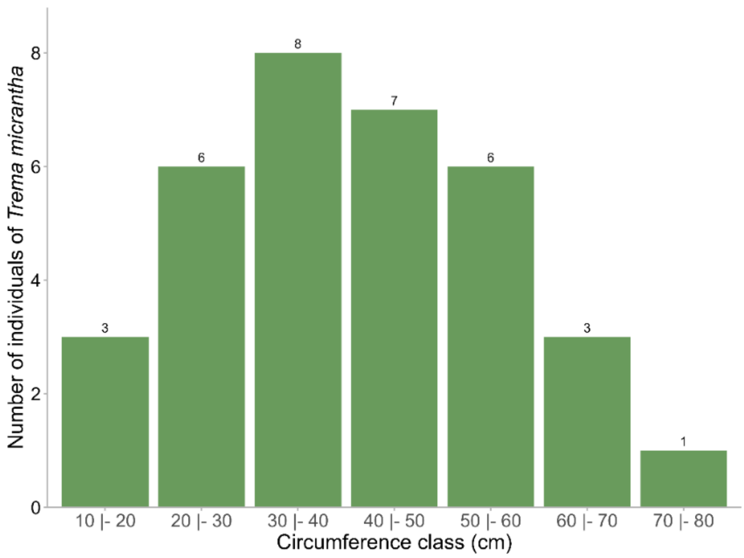
**Figure 2** – Frequency distribution of individuals in the natural regeneration study area.




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.

Revista Thema
v.24 | n.2 | 2025
p.1-16
DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

### 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 (pH-$H_2O$ = 5.77), intermediate levels of the Organic Matter (OM = 3.86), Base sum (BS = 2.33) and effective Cation Exchange Capacity (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 | Total-N | pH | P | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | H+Al | BS | CEC | V | OM | Cu | Mn | Fe | Zn |
| (0-20cm) | (dag/kg) | ($H_2O$) | (mg/dm³) | | (cmolc/dm³) | | | | | % | (dag/kg) | (mg/dm³) | | | |
| 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 | 11.09 |
| 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 | 1.25 |
| 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 | 17.35 |

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

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

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.

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

## 5. ACKNOWLEDGMENTS

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) by research fellowships for the authors and to the Companhia Brasileira de Alumínio (CBA) for provided infrastructure and financial support for the project.

## 6. REFERENCES

AAVIK, T.; HELM, A. Restoration of plant species and genetic diversity depends on landscape scale dispersal. **Restoration Ecology**, v. 26, p. S92-S102, 2018. https://doi.org/10.1111/rec.12634

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. **Meteorologische zeitschrift**, v. 22, n. 6, p. 711-728, 2013. https://doi.org/10.1127/0941-2948/2013/0507

ANGIOSPERM PHYLOGENY GROUP et al. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG IV. **Botanical journal of the Linnean Society**, v. 181, n. 1, p. 1-20, 2016. https://doi.org/10.1111/boj.12385

ANM – AGÊNCIA NACIONAL DE MINERAÇÃO. *Anuário Mineral Brasileiro: principais substâncias metálicas 2024*. Brasília: ANM, 2025. 26 p. Disponível em: https://www.gov.br/anm/pt-br/assuntos/economia-mineral/publicacoes/anuario-mineral/anuario-mineral-brasileiro/anuario-mineral-brasileiro-principais-substancias-metalicas-2024. Acesso em: 03 abril. 2025.

ARAÚJO, F. S. et al. Estrutura da vegetação arbustivo-arbórea colonizadora de uma área degradada por mineração de caulim, Brás Pires, MG. **Revista Árvore**, v. 30, p. 107-116, 2006. https://doi.org/10.1590/S0100-67622006000100013

BALESTRIN, D. et al. Phytosociological study to define restoration measures in a mined area in Minas Gerais, Brazil. **Ecological Engineering**, v. 135, p. 8-16, 2019a. https://doi.org/10.1016/j.ecoleng.2019.04.023

BALESTRIN, D. et al. Relationship between soil seed bank and canopy coverage in a mined area. **Revista Árvore**, v. 43, p. e430403, 2019b. https://doi.org/10.1590/1806-90882019000400003

BALESTRIN, D.; MARTINS, S. V.; FONSECA, C. A. Ecological restoration and forest coverage advancement in a region influenced by bauxite mining, Minas Gerais, Brazil. **Recent Advances in Ecological Restoration**. New York: Nova Science Publishers, p. 143-154, 2020.

BARBOSA, R. S et al. Restoration of degraded areas after bauxite mining in the eastern Amazon: Which method to apply?. Ecological Engineering, v. 180, p. e106639, 2022. https://doi.org/10.1016/j.ecoleng.2022.106639

BIZUTI, Denise TG et al. Recovery of soil phosphorus on former bauxite mines through tropical forest restoration. **Restoration Ecology**, v. 28, n. 5, p. 1237-1246, 2020. https://doi.org/10.1111/rec.13194

BORGES, S. R. **Qualidade do solo em áreas de restauração com forrageiras e cafeeiro pós-mineração de bauxita**. 2013. 111f. Tese (Programa de Pós-graduação em Solos e Nutrição de Plantas) - Universidade Federal de Viçosa, Viçosa-MG, 2013.

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

BORGES, S. R. et al. Practices for rehabilitating bauxite-mined areas and an integrative approach to monitor soil quality. **Land Degradation & Development**, v. 30, n. 7, p. 866-877, 2019. https://doi.org/10.1002/ldr.3273

CAVALCANTE, D. M.; SILVA, I. R.; OLIVEIRA, T. S. Soil quality indicators for monitoring the short-term effects of mined soil rehabilitation strategies for bauxite. **Revista Brasileira de Ciência do Solo**, v. 47, p. e0220126, 2023. https://doi.org/10.36783/18069657rbcs20220126

CHAZDON, R. L.; GUARIGUATA, M. R. Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. **Biotropica**, v. 48, n. 6, p. 716-730, 2016. https://doi.org/10.1111/btp.12381

CHAZDON, R. L. et al. **Partnering with nature: the case for natural regeneration in for-est and landscape restoration**. FERI Policy Brief, Montreal Canada. Montreal, Canada: Forest Ecosystem Restoration Initiative, 2017.

CHAZDON, R. L. et al. Monitoring recovery of tree diversity during tropical forest restoration: lessons from long-term trajectories of natural regeneration. **Philosophical Transactions of the Royal Society B**, v. 378, n. 1867, p. e20210069, 2023. https://doi.org/10.1098/rstb.2021.0069

CORRÊA, R. S.; MELO-FILHO, B. Levantamento florístico do estrato lenhoso das áreas mineradas no Distrito Federal. **Revista Árvore**, v. 31, p. 1099-1108, 2007. https://doi.org/10.1590/S0100-67622007000600015

COSIMO, L. H. E.; MARTINS, S. V.; GLERIANI, J. M. Suggesting priority areas in the buffer zone of Serra do Brigadeiro State Park for forest restoration compensatory to bauxite mining in Southeast Brazil. **Ecological Engineering**, v. 170, p. e106322, 2021. https://doi.org/10.1016/j.ecoleng.2021.106322

COVERDALE, T. C.; DAVIES, A. B. Unravelling the relationship between plant diversity and vegetation structural complexity: A review and theoretical framework. **Journal of Ecology**, v. 111, n. 7, p. 1378-1395, 2023. https://doi.org/10.1111/1365-2745.14068

CROUZEILLES, R. et al. Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. **Science advances**, v. 3, n. 11, p. e1701345, 2017. https://doi.org/10.1126/sciadv.1701345

FIGUEIREDO, Maurílio A. et al. Topsoil volume optimization in the restoration of post-mined areas. **Restoration Ecology**, v. 32, n. 7, p. e14222, 2024. https://doi.org/10.1111/rec.14222

FLORA E FUNGA DO BRASIL. Jardim Botânico do Rio de Janeiro, 2023. Disponível em: http://floradobrasil.jbrj.gov.br/.

FONSECA, D. A. et al. Evaluation of the natural regeneration in a restoration planting area and in a reference riparian forest. **Ciência Florestal**, v. 27, n. 2, p. 521-534, 2017. http://dx.doi.org/10.5902/1980509827733

FONSECA, W. S.; MARTINS, S. V. Monitoramento de fauna como indicador de restauração florestal de uma área em ambiente de mineração de bauxita na Zona da Mata Mineira. In: Oliveira, R.J.

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

(Org.). **Águas e Florestas: Desafios Para Conservação e Utilização**. 1ed. Guarujá, SP: Editora Científica Digital, 2021, p. 340-357. https://doi.org/10.37885/210404406

FONSECA, W. S. et al. Green Manure as an Alternative for Soil Recovery in a Bauxite Mining Environment in Southeast Brazil. **Floresta e Ambiente**, v. 30, p. e20220041, 2023. https://doi.org/10.1590/2179-8087-FLORAM-2023-0041

FONSECA, W. S. et al. Complementing seedling planting with nucleation techniques increases forest restoration potential in areas around bauxite mining. **Land Degradation and Development**, v. 35, n. 9, p. 3075–3089, 2024a. https://doi.org/10.1002/ldr.5118

FONSECA, W. S. et al. Understanding the seasonal growth patterns of seedlings in forest restoration of post-bauxite mining area: insights for monitoring in the Atlantic Forest. **REVISTA DELOS**, v. 17, n. 58, p. e1606-e1606, 2024b.

GANDOLFI, S.; LEITÃO-FILHO, H. F.; BEZERRA, C. L. F. Levantamento florístico e caráter sucessional das espécies arbustivo-arbóreas de uma floresta mesófila semidecídua no município de Guarulhos, SP. **Revista brasileira de biologia**, v. 55, n. 4, p. 753-767, 1995.

GUIMARÃES, J. C. C. **Restauração Ecológica de áreas mineradas de bauxita na Mata Atlântica.** 2015. 125f. Tese (Programa de Pós-graduação em Engenharia Florestal) - Universidade Federal de Lavras, Lavras – MG, 2015.

IBGE. **Manual Técnico da Vegetação Brasileira**. 2ª ed. Manuais Técnicos em Geociências. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística. 2012.

IUSS Working Group WRB. World Reference Base for Soil Resources. **International soil classification system for naming soils and creating legends for soil maps**. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria, 2022. Disponível em: < https://www.isric.org/sites/default/files/WRB_fourth_edition_2022-12-18.pdf>.

KAMBLE, P. H.; BHOSALE, S. M. Assessment of impact of bauxite mining on environment. **i-Manager's Journal on Future Engineering and Technology**, v. 14, n. 4, p. 14, 2019. http://doi.org/10.22214/ijraset.2019.1017

KLEIN, A. S. et al. Regeneração natural em área degradada pela mineração de carvão em Santa Catarina, Brasil. **Rem: Revista Escola de Minas**, v. 62, p. 297-304, 2009. https://doi.org/10.1590/S0370-44672009000300007

KÖPPEN W. **Climatologia: con un estudio de los climas de la tierra**. México: Fondo de Cultura Econômica, 1948.

LATAWIEC, A. E. et al. Natural regeneration and biodiversity: a global meta-analysis and implications for spatial planning. **Biotropica**, v. 48, n. 6, p. 844-855, 2016. https://doi.org/10.1111/btp.12386

LEI, K.; PAN, H.; LIN, C.. A landscape approach towards ecological restoration and sustainable development of mining areas. **Ecological Engineering**, v. 90, p. 320-325, 2016. https://doi.org/10.1016/j.ecoleng.2016.01.080

DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

LIMA, M. T. et al. The dynamics of the substrate recovery of waste dumps in calcary mining under natural regeneration. **Cerne**, v. 24, p. 18-26, 2018. https://doi.org/10.1590/01047760201824012476

MACHADO, D. L. et al. Matéria orgânica e fertilidade do solo em diferentes estágios sucessionais de floresta estacional semidecidual. **Revista Caatinga** , v. 32, p. 179-188, 2019.

MARTINS, S. V. Alternative forest restoration techniques. In: VIANA, H. (Ed.). **New perspectives in forest science**. 1st ed. London: IntechOpen, 2018. p. 131-148. https://doi.org/10.5772/intechopen.72908

MARTINS, S. V. et al. Restoration of tree and shrub diversity post bauxite mining, in the Southeastern Region of Minas Gerais, Brazil. In: VLIEGER, K, (Ed.). **Recent Advances in Ecological Restoration**. 1 ed. New York: Nova Science Publishers, 2020. p. 33-62, 2020.

MARTINS, S. V. et al. Soil Seed Banks in Two Environments of Forest Restoration Post Bauxite Mining: Native Tree Plantation and Natural Regeneration. **Research in Ecology**, v. 3, n. 1, p. 1-13, 2021. https://doi.org/10.30564/re.v3i1.2631

MARTINS, S. V et al. Reflorestamento com mudas altas: uma inovação da restauração florestal na mineração de bauxita em Minas Gerais. In: Oliveira, R.J. (Org.). **Engenharia florestal: contribuições, análises e práticas em pesquisa**. Guarujá: Editora Científica Digital, 2022. p. 213-230. https://dx.doi.org/10.37885/220308108

MIRANDA-NETO, A et al. Natural regeneration in a restored bauxite mine in southeast Brazil. **Bosque**, v. 35, n. 3, p. 377-389, 2014. http://dx.doi.org/10.4067/S0717-92002014000300012

NETO, A. B. B. et al. Natural regeneration for restoration of degraded areas after bauxite mining: A case study in the Eastern Amazon. **Ecological Engineering**, v. 171, p. 106392, 2021. https://doi.org/10.1016/j.ecoleng.2021.106392

OLIVEIRA, A. et al. Semeadura direta e plantio de mudas para recuperação de nascentes no rio Piauitinga, município de Salgado, Sergipe, Brasil. **Revista Thema**, v. 21, n. 1, p. 289-302, 2022. http://dx.doi.org/10.15536/thema.V21.2022.289-302.2473

OLUWAJUWON, T. V. et al. Bibliometric and literature synthesis on assisted natural regeneration: an evidence base for forest and landscape restoration in the tropics. **Frontiers in Forests and Global Change**, v. 7, p. 1412075, 2024. https://doi.org/10.3389/ffgc.2024.1412075

OLUWAJUWON, T. V. et al. Assisted natural regeneration for tropical forest and landscape restoration in the Philippines: Implementation, motivations, challenges and future directions. **Trees, Forests and People**, p. 100896, 2025. https://doi.org/10.1016/j.tfp.2025.100896

ONÉSIMO, C. M. G. et al. Ecological succession in areas degraded by bauxite mining indicates successful use of topsoil. **Restoration Ecology**, v. 29, n. 1, p. e13303, 2021. https://doi.org/10.1111/rec.13303

Revista Thema
v.24 n.2 2025
p.1-16
DOI: http://dx.doi.org/10.15536/revistathema.24.2025.3568
ISSN: 2177-2894 (online)

R-CORE TEAM. **R: A language and environment for statistical computing.** Version 4.4.1. R Foundation for Statistical Computing, 2024. Available at: https://www.R-project.org. Accessed on: 30 Jul. 2024.

RAJAPAKSHE, R. et al. Restoring a dry tropical forest through assisted natural regeneration: enhancing tree diversity, structure, and carbon stock. **Trees, Forests and People**, v. 17, p. 100616, 2024. https://doi.org/10.1016/j.tfp.2024.100616

REIJ, C.; GARRITY, D. Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. **Biotropica**, v. 48, n. 6, p. 834-843, 2016. https://doi.org/10.1111/btp.12390

RIBEIRO, A. C.; GUIMARÃES, P. T. G.; VENEGAZ, V. H. A. **5ª Aproximação-Recomendações para o uso de corretivos e fertilizantes em Minas Gerais**. Viçosa – MG: Editora UFV, 1999.

ROCHA, M. H. F. et al. Análise fitossociologia e valor de importância em carbono de áreas em restauração florestal na Serra da Mantiqueira, Minas Gerais, Brasil. **Delos: Desarrollo Local Sostenible**, v. 16, n. 47, p. 2526-25248, 2023. https://doi.org/10.55905/rdelosv16.n47-002

ROZENDAAL, D. M. A. et al. Biodiversity recovery of Neotropical secondary forests. **Science advances**, v. 5, n. 3, p. eaau3114, 2019. https://doi.org/10.1126/sciadv.aau3114

SANTOS, H. G. et al. **Sistema brasileiro de classificação de solos**. Brasília (DF): Embrapa. 2018

SHEPHERD, G. J. Fitopac. Version 2.1. Campinas - SP: Departamento de Botânica, Universidade Estadual de Campinas, 2010.

SILVA, K. A et al. Influence of Environmental Variables on the Natural Regeneration of a Forest under Restoration after Bauxite Mining and in a Reference Ecosystem in Southeastern Brazil. **Research in Ecology**, v. 2, n. 4, p. 31-41, 2020. https://doi.org/10.30564/re.v2i4.2609

SOIL SURVEY STAFF. Keys to Soil Taxonomy. 13th ed. USDA-Natural Resources Conservation Service, 2022.

SOUZA, R. S. et al. Bauxite mining in the Amazon: impacts of environmental recovery methods on soil organic matter and physical attributes. **Landscape and Ecological Engineering**, p. 1-12, 2025. https://doi.org/10.1007/s11355-025-00669-2

SPAIN, A. V. et al. Phosphorus dynamics in a tropical forest soil restored after strip mining. **Plant and Soil**, v. 427, p. 105-123, 2018. https://doi.org/10.1007/s11104-018-3668-8

STRASSBURG, B. B. N. et al. The role of natural regeneration to ecosystem services provision and habitat availability: a case study in the Brazilian Atlantic Forest. **Biotropica**, v. 48, n. 6, p. 890-899, 2016. https://doi.org/10.1111/btp.12393

SUGANUMA, M. S. et al. Changes in plant species composition and functional traits along the successional trajectory of a restored patch of Atlantic Forest. **Community Ecology**, v. 15, p. 27-36, 2014. https://doi.org/10.1556/comec.15.2014.1.3

**DOI**: http://dx.doi.org/10.15536/revistathema.24.2025.3568
**ISSN**: 2177-2894 (online)

SUGANUMA, M. S.; DURIGAN, G. Indicators of restoration success in riparian tropical forests using multiple reference ecosystems. **Restoration Ecology**, v. 23, n. 3, p. 238-251, 2015. https://doi.org/10.1111/rec.12168

USGS. Shuttle Radar Topography Mission (SRTM). United States Geological Survey, 2000. Available from: https://lta.cr.usgs.gov/SRTM

USGS. **Mineral commodity summaries 2024**: U.S. Geological Survey, 212 p., 2024 https://doi.org/10.3133/mcs2024

VALOIS-CUESTA, H.; MARTÍNEZ-RUIZ, C. Vulnerabilidad de los bosques naturales en el Chocó biogeográfico colombiano: actividad minera y conservación de la biodiversidad. **Bosque** (Valdivia), v. 37, n. 2, p. 295-305, 2016. http://dx.doi.org/10.4067/S0717-92002016000200008

VAN DER PIJL, Leendert et al. **Principles of dispersal in higher plants**. Berlin: Springer-Verlag, 1982.

VILLA, P. M. et al. Taxonomic and functional beta diversity of woody communities along Amazon forest succession: The relative importance of stand age, soil properties and spatial factor. **Forest Ecology and Management**, v. 482, p. 118885, 2021. https://doi.org/10.1016/j.foreco.2020.118885

WICKHAM, H. ggplot2: Elegant graphics for data analysis. Springer International Publishing, 2016.

WILSON, S. J. et al. Assisted natural regeneration. A guide for restoring tropical forests. **Conservation International, Arlington, Virginia**, 2022.

WU, Yuhang et al. How do species richness and its component dependence vary along the natural restoration in extremely heterogeneous forest ecosystems?. **Journal of environmental management**, v. 354, p. 120265, 2024. https://doi.org/10.1016/j.jenvman.2024.120265

XIAO, L. et al. Long-term effects of vegetational restoration on soil microbial communities on the Loess Plateau of China. **Restoration Ecology**, v. 24, n. 6, p. 794-804, 2016. https://doi.org/10.1111/rec.12374

YANG, Y. et al. Large ecosystem service benefits of assisted natural regeneration. **Journal of Geophysical Research: Biogeosciences**, v. 123, n. 2, p. 676-687, 2018. https://doi.org/10.1002/2017JG004267

YANG, Z. et al. Does the universal adaptive strategy theory apply to natural regeneration in heterogeneous subtropical karst forests?. **Ecological Indicators**, v. 165, p. 112168, 2024. https://doi.org/10.1016/j.ecolind.2024.112168

**Submission: 27/10/2023**

**Accepted: 23/09/2025**