# Relationship between soil seed bank and forest restoration techniques on areas around bauxite mining environment

Wesley da Silva Fonseca[1], Sebastião Martins[1], Pedro Manuel Villa[1], and Enzo Mauro Fioresi[1]

[1]Universidade Federal de Vicosa Departamento de Engenharia Florestal

January 27, 2023

**Abstract**

The soil seed bank is one of the most important ecological indicators to evaluate and monitor the ecological restoration process of plant communities. We aimed to evaluate the influence of ecological restoration techniques on the plant community diversity and composition and functional group composition of the soil seed bank in two bauxite mining areas under compensatory restoration, Southeast Brazil. 30 soil samples were collected in each area (Area_A – Forest restoration by planting seedlings and nucleation techniques and Area_B – just restoration by planting seedlings). The samples were transported to a shade house and evaluated for six months, where germinated individuals were counted and identified weekly. The results indicated that the soil seed banks of the two areas are floristically similar (with a predominance of pioneer, herbaceous and native origin species), which show a higher natural regeneration potential. However, the higher species richness and abundance of zoochoric individuals in Area_A demonstrate that nucleation techniques, such as topsoil transposition and direct seeding were efficient to increase the recovery potential re-establishment. In the early successional stages, restoration techniques are more determinant in the functional group composition than in the floristic composition of the soil seed bank.

**Relationship between soil seed bank and forest restoration techniques on areas around bauxite mining environment**

**Abstract:** The soil seed bank is one of the most important ecological indicators to evaluate and monitor the ecological restoration process of plant communities. We aimed to evaluate the influence of ecological restoration techniques on the plant community diversity and composition and functional group composition of the soil seed bank in two bauxite mining areas under compensatory restoration, Southeast Brazil. 30 soil samples were collected in each area (Area_A – Forest restoration by planting seedlings and nucleation techniques and Area_B – just restoration by planting seedlings). The samples were transported to a shade house and evaluated for six months, where germinated individuals were counted and identified weekly. The results indicated that the soil seed banks of the two areas are floristically similar (with a predominance of pioneer, herbaceous and native origin species), which show a higher natural regeneration potential. However, the higher species richness and abundance of zoochoric individuals in Area_A demonstrate that nucleation techniques, such as topsoil transposition and direct seeding were efficient to increase the recovery potential re-establishment. In the early successional stages, restoration techniques are more determinant in the functional group composition than in the floristic composition of the soil seed bank.

**Keywords:** bioindicators - ecological restoration - environmental compensation - nucleation techniques - recovery of degraded areas - sustainability.

## INTRODUCTION

Mining has great relevance to the Brazilian economy, estimates by the National Mining Agency indicate that mineral production in 2020 contributed US$ 43.7 billion, representing 2.4% of Brazil's GDP (USGS 2022). In this sense, the Southeast of Brazil, more specifically the state of Minas Gerais, concentrates approximately 200 thousand direct jobs related to mining sector, in addition to having one of the highest revenues in the country in the Financial Compensation for the Exploration of Resources (CFEM), with a percentage of 44.7% (IBRAM 2022). In addition to socio-economic contributions, mining companies are aligned with the commitments of the UN Decade on Ecosystem Restoration and The Sustainable Development Goals (SDGS) (UN, 2022). In order for mining to be sustainable, companies carry out forest conservation and forest restoration actions, a great example of this initiative is the mining of bauxite in the "Zona da Mata" region of Minas Gerais State, Brazil (Martins et al., 2020; Fonseca 2021).

Numerous bioindicators have demonstrated the positive effects of bauxite mining in Minas Gerais State, such as the increase in regional forest cover compared to before mining activities, due to compensatory plantings, and the reduction of soil loss through erosive processes (Balestrin et al., 2018). In addition, some authors highlighted the recovery of the diversity of tree species native to the Atlantic Forest (Martins et al., 2020), the restoration of functional relationships between fauna and flora (Volpato et al., 2018; Fonseca & Martins 2021), the efficiency of nucleation and rapid soil cover by green manures (Fonseca 2021; Fonseca et al., 2023), the recovery of soil fertility (Silva et al., 2018) and the potential for natural regeneration of areas (Miranda-Neto et al., 2014a; Silva et al., 2016; Silva et al., 2020; Martins et al., 2021). In this sense, forest restoration projects in the bauxite mining environment in the state of Minas Gerais are contributing to the formation of secondary forests with high diversity (Fonseca 2021, Martins et al., 2022). Recent studies highlight the importance of secondary forests recovery (i.e., biodiversity and ecosystem services) and as important strategies for mitigating climate change (Lewis et al., 2015; Rezende et al., 2018; Vilas Boas et al., 2018; Rozendaal et al., 2019; Poorter et al., 2019; Lima et al., 2020; Sarmento et al., 2021; Romanelli et al., 2022; Bizuti et al., 2022; Martins et al., 2022; Jakovac et al., 2022). Thus, the passive restoration method promotes vegetation spontaneously recovery by natural regeneration, and is a cost-effective method to the ecological restoration of tropical ecosystems (Crouzeilles et al., 2017; Holl 2017; Tonetti et al., 2022). In this context, monitoring ecological indicators of the Atlantic Forest after disturbances contributes to a better understanding of restoration practices (Balestrin et al., 2019; Borges et al., 2019; Martins et al., 2020; Campanharo et al., 2021; Bizuti et al., 2022).

The soil seed bank is one of the most important ecological indicators for the evaluation and monitoring of the plant communities' recovery (Balestrin et al., 2019; Martins et al., 2021). The soil seed bank represents a stock of seeds on the surface layer of the soil and/or litter, which persist dormant until environmental conditions are favorable for germination (Sarmento et al., 2021; Martins et al., 2021). The soil seed banks composition is defined by local environmental conditions (i.e., luminosity, temperature, water availability) and by seed dispersal from aboveground vegetation (Martins et al., 2015; Shi et al., 2022). Therefore, the soil seed bank is essential for the maintenance of species diversity (i.e., species richness, species composition, dominance and evenness) during natural forest regeneration after disturbances (Balestrin et al., 2019; Silva et al., 2021b; Martins et al., 2021). Most of these studies on soil seed bank have focused mainly on the processes influencing the changes in community composition and species richness in disturbed areas compared to reference ecosystems (Miranda-Neto et al., 2016; Silva et al., 2019; Adjalla et al., 2022). Nevertheless, this classical approach can limit disentangling processes on plant communities during ecological restoration. For example, two plant communities can display equal species richness but with considerable differences in their dominance and evenness, which is a fundamental premise for conservation biology and plant community assembly (Jost, 2006, 2007; Chao et al., 2014, Mori et al., 2018; Larson & Suding., 2022).

In this context, understanding the soil seed bank based on different functional groups (i.e., dispersal syndromes, regeneration strategies) that can directly influence the pattern of species richness is possible to define restoration techniques (Martins 2018; Shi et al., 2022). Thus, beyond these restoration techniques (seedling planting, direct seeding, topsoil transposition, green manure, artificial perches), the variation in the relative importance of functional groups (i.e., seed dispersal syndrome, regeneration strategies) on species richness its essential to ecosystem recovery (Carlucci et al., 2020; Villa et al., 2021). For example, the selection of zoochoric species can stimulate fauna-flora relationships and, consequently, favor seed dispersal (Coelho et al., 2022). The nucleation techniques such as direct seeding and topsoil transposition can help in the arrival of new propagules in the area under restoration and contribute to increasing species richness (Fonseca 2021). During early successional stages of secondary forest after disturbances exhibits fast-growth and light-demanding pioneer species with short life cycles along with dominance of anemochoric and autochoric (non-zoochoric) pioneer species (Chazdon 2014; Santo-Silva et al., 2016). Then, shade-tolerant and long-lived species gradually dominate the forest canopy, along late-successional stages (Chazdon, 2014; Poorter et al., 2019). The non-zoochoric species occurrence also decreases during late-successional stages, while the dominance of zoochoric species increases (e.g. Santo-Silva et al., 2016).

Studies on soil seed banks in mining areas are concentrated in places where there was direct mineral exploration, through floristic approaches and phytosociological surveys (Silva et al., 2019; Onésimo et al., 2021). However, there are many areas around the mining that suffer impacts, mainly related to the suppression of vegetation and changes in soil layers (Martins et al., 2020; Spletozer et al., 2021). Usually, the areas destined for the administrative sectors, the parking lots and other structures of the mining company have compacted soil and absence of the organic layer (O horizon) and the topsoil layer (A horizon) (Fonseca 2021). To ensure sustainability companies commonly include these areas in the environmental compensation program; however, studies in areas surrounding mining and carried out through functional group approaches are still limited. In this context, functional approaches to the soil seed bank are essential to better understand the ecological mechanisms that guide aboveground successional processes in tropical secondary forests (Villa et al., 2020; Sarmento et al., 2021; Villa et al., 2021).

Thus, we aimed to evaluate the influence of ecological restoration techniques on the plant community diversity and composition and functional groups composition of the soil seed bank on two bauxite mining areas under compensatory restoration in Southeast Brazil.

## MATERIAL AND METHODS

### Study area

The study was carried out in the municipality of Miraí, in the Southeast of the state of Minas Gerais, Brazil (Figure 1), in two adjacent areas: Area_A – Forest restoration by planting seedlings and nucleation techniques (21º 4 ' 5.40" S and 42º 33' 27.83" W) and Area_B – just forest restoration by planting seedlings (21º 4' 5" S and 42º 33' 31" W).

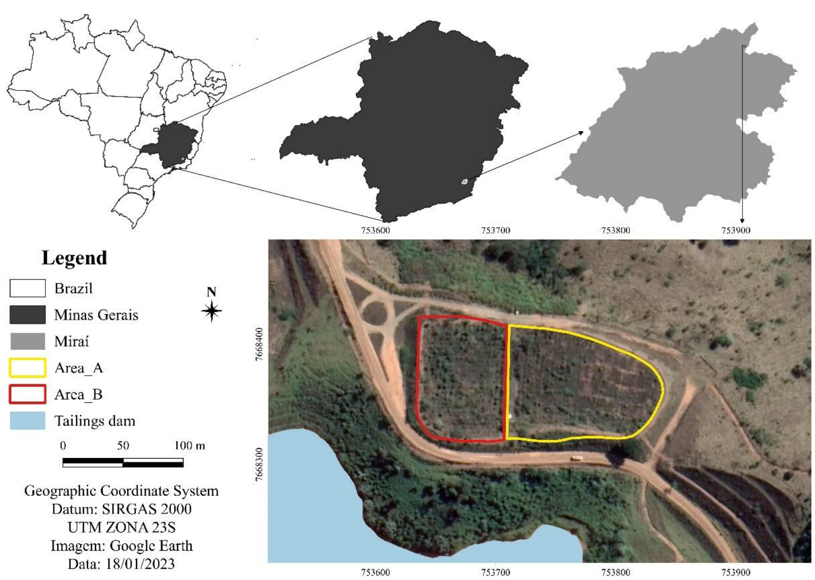


**Figure 1** – Location of the study areas in Miraí, Minas Gerais, Brazil

The characteristic vegetation of this region is classified as Seasonal Semideciduous Forest, inserted in the Atlantic Forest Domain (IBGE 2012). According to Koppen's classification, the climate in the region is Cwa type, characterized as humid temperate with dry winter and hot summer, with an annual precipitation of 1,564 mm and an annual mean temperature of 23.5 ºC. According to the Brazilian Soil Classification System, the predominant soil in the region is the typical dystrophic Yellow-Red Latosol and relief is characterized as wavy solid and mountainous (Santos et al., 2018).

This study was conducted in adjacent areas, which until the end of 2016 was used for the administrative office sector of Companhia Brasileira de Alumínio (CBA) (Figure 1). With the change in the location of the company's administrative office sector, all buildings were removed and, consequently, the layer of soil exposed to the surface (subsoil) was highly compacted and had low levels of organic matter and nutrients. That is, it is worth noting that both areas did not have the surface horizon of the soil, considered the fertile layer. Thus, these areas were included in the company's environmental compensation program for bauxite mining (Fonseca 2021).

As restoration measures, soil preparation was carried out in both areas with a ripper subsoiler at a depth of 60 cm, and acidity correction and fertilization were carried out in the total area. In sequence, the sowing of three species of green manures was carried out: *Cajanus cajan* L. Millsp; *Crotalaria juncea* L. and *Stylosanthes guianensis* Aubl. Sw and seedlings of 18 native tree species with different successional characteristics were planted (Table 1). In addition to planting seedlings, in Area_A, nucleation techniques were also implemented between the lines, such as: transposition of topsoil, direct sowing of native tree species and implantation of artificial perches.

**Table 1.** Floristic list of species planted in the study area.

| **Botanical family** | **Species** | **SC** | **DS** |
|---|---|---|---|
| Bignoniaceae | *Handroanthus heptaphyllus* (Vell.) Mattos | LS | Ane |
| | *Handroanthus impetiginosus* (Mart. Ex DC.) Mattos | LS | Ane |
| | *Tabebuia roseoalba* (Ridl.) Sandwith | ES | Ane |
| | *Jacaranda micrantha* Cham | ES | Ane |
| Cannabaceae | *Trema micrantha* (L.) Blume | P | Zoo |
| Euphorbiaceae | *Alchornea glandulosa* Poepp. | P | Zoo |
| | *Sapium glandulosum* (L.) Morong | P | Zoo |
| Fabaceae | *Bauhinia forficata* Link | P | Aut |
| | *Caesalpinia pluviosa* DC. | ES | Aut |
| | *Clitoria fairchildiana* R.A.Howard | ES | Aut |
| | *Senegalia polyphylla* (DC.) Britton & Killip | P | Aut |
| Malvaceae | *Pseudobombax grandiflorum (Cav.) A.Robyns* | P | Ane |
| Melastomataceae | *Tibouchina granulosa* (Desr.) Cogn. | P | Ane |
| Myrtaceae | *Psidium guajava L.* | P | Zoo |
| Solanaceae | *Solanum pseudoquina* A. St.-Hil. | ES | Zoo |
| Urticaceae | *Cecropia glaziovii* Snethl. | P | Zoo |
| | *Cecropia hololeuca* Miq. | P | Zoo |
| Verbenaceae | *Citharexylum myrianthum* Cham. | ES | Zoo |

SC: Successional category (P: Pioneer, ES: Early secondary, LS: Late secondary); DS: Dispersal syndrome (Ane: anemochory, Aut: autochory, Zoo: zoochory).

For the edaphic characterization of the areas (before and after the implementation of forest restoration techniques), chemical analyzes of the soil were carried out at different times (2016 and 2021), as shown in Table 2. The composite samples obtained in Area_A and Area_B were sent to the Soil Laboratory of the

Federal University of Viçosa for the analyses. The results were interpreted according to the Minas Gerais Corrective and Fertilizer Recommendation Guide (Ribeiro et al., 1999). In Area_A and Area_B after the removal of administrative structures (end of 2016), it is possible to verify low soil fertility and, mainly, low levels of organic matter (OM). After 4 years of implementation of restoration techniques, an increase in pH, P, K, $Ca^{2+}$,$Mg^{2+}$, SB and P-Rem properties and a reduction in acidity were observed in both areas. Also noteworthy is the considerable increase in soil organic matter, total-N and base saturation (V%), which show an improvement in soil fertility.

**Table 2.** Variation of soil chemical parameters in Area_A and Area_B between the years 2016 (grey) and 2021 (white).

| **Sample** | **pH** | **Total-N** | **OM** | **P** | **K** | **$Ca^{2+}$** | **$Mg^{2+}$** | **H+Al** | **SB** | **CEC** | **V** | **P R** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (0-20 cm) | $H_20$ | dag/kg | dag/kg | mg/dm3 | mg/dm3 | $cmol_c/dm3$ | $cmol_c/dm3$ | $cmol_c/dm3$ | $cmol_c/dm3$ | $cmol_c/dm3$ | % | m |
| Area_A (2016) | 5,39 | 0,022 | 0,25 | 4,4 | 21 | 0,59 | 0,18 | 1,5 | 0,82 | 2,32 | 35,3 | 1 |
| Area_A (2021) | 6,86 | 0,213 | 5,45 | 335,0 | 90 | 4,43 | 1,90 | 1,4 | 6,56 | 7,96 | 82,4 | 2 |
| Area_B (2016) | 5,47 | 0,022 | 0,51 | 3,4 | 26 | 1,19 | 0,17 | 1,6 | 1,43 | 3,03 | 47,2 | 1 |
| Area_B (2021) | 7,40 | 0,154 | 4,39 | 328,8 | 76 | 4,96 | 1,45 | 0,6 | 6,60 | 7,20 | 91,7 | 2 |

OM (Organic Matter); Total-N (Total Nitrogen); P (Phosphorus); K (Potassium); $Ca^{2+}$ (Calcium); $Mg^{2+}$(Magnesium); H + Al (Potential acidity); SB = (Sum of bases); CEC – (Cation Exchange Capacity at pH 7.0); V (Base Saturation Index); P-rem (Remaining Phosphorus).

### Field Procedures

30 soil samples were collected in each area (Area_A and Area_B), in the most representative way possible, totaling 60 samples. At each point, a 40 x 40 cm PVC template was used to collect surface soil samples at a depth of 5.0 cm, disregarding the litter. The soil samples were packed in plastic bags, properly identified and transported to the shade house of the Research Nursery at the Federal University of Viçosa, in Minas Gerais (coverage with 50% shading). The samples were placed in plastic trays measuring 0.25 x 0.30 x 0.05 m, with holes for drainage of excess water. Four trays with sterilized sand were placed on the bench in order to control external contamination. Soil samples were under programmed sprinkler irrigation (four daily irrigations lasting three minutes each) for a period of six months. All emerged individuals were identified, counted and removed weekly.

### Classification of species

The taxonomic identification of the species was performed according to the Angiosperm Phylogeny Group (APG IV) and the species nomenclatures were verified using the database of The Plant List website. The species were classified in successional category as: pioneer (P), early secondary (ES), late secondary (LS) and not classified (Nc). As for the syndrome of dispersion of propagules in: anemochoric (Ane), autochoric (Aut) and zoochoric (Zoo). In addition, the species were also classified according to their way of life as herbaceous (H), shrub (S), tree (T) and vine (V) and according to their origin as: native (N) and exotic (E).

### Data processing and analysis

Phytosociological parameters such as relative density (RelDe) and relative frequency (RelFr) were calculated according to the criteria proposed by Mueller-Dombois and Ellenberg. The Shannon-Wiener diversity index (H') and the Pielou equability index (J') were calculated using the FITOPAC 2.1 software (Shepherd 2010).

One-way ANOVA analysis of variance was used to compare mean species richness and mean individual abundance, followed by a subsequent Tukey test for independent samples ($p < 0.05$) (Crawley 2013). To perform the analysis and statistical evaluation, the R software version 4.1.3 and the Vegan package (R Core Team, 2022) were used.

The rarefaction approach was used to estimate species richness and compare areas under restoration. In addition, the comparison of the functional composition of soil seed bank species between areas, based on the dispersion syndrome, was estimated using rarefaction and extrapolation curves. The curves were constructed with Hill numbers: species richness ($q = 0$), exponential of Shannon entropy (Shannon's diversity, $q = 1$), and inverse Simpson concentration (Simpson diversity, $q = 2$), for both individual-based rarefaction and extrapolation curves (Diniz & Villa 2020). Extrapolations were made from a presence/absence data matrix (Colwell et al., 2012). These estimates were obtained using the "iNEXT" package (Hsieh et al., 2016). All three Hill numbers were estimated as the mean of 100 replicate bootstrapping runs to estimate 95% confidence intervals. When the 95% confidence intervals did not overlap, species number differed significantly at $p < 0.05$ (Colwell et al., 2012; Diniz & Villa 2020).

Non-metric multidimensional scaling (NMDS) was used to analyze the variation in floristic composition between areas, using the "metaMDS" function and the Jaccard similarity based on presence and absence data (Oksanen et al., 2018). Then, multivariate permutational analysis of variance (PERMANOVA, 9999 permutations) was used to test differences in species composition, using the "adonis" function, available in the "vegan" package (Oksanen et al., 2018; Diniz & Villa 2020).

The plots were also grouped based on the abundance data of each species, using a Bray-Curtis matrix (floristic dissimilarity) and UPGMA method (Unweighted Pair Group Method with Arithmetic Mean). The Sørensen index was used to estimate the degree of floristic similarity between plots. All analyzes were performed using R (R Core Team, 2022), except the UPGMA Two-Way analysis for Cluster, which used the PC-Ord 5.14 program (Villa et al., 2019).

## RESULTS

In the soil seed bank of Area_A (forest being restored by planting seedlings and nucleation techniques) 1,178 individuals (523.5 individuals $m^{-2}$) were recorded, belonging to 43 species and 18 botanical families, with (H') = 2.970 and (J') = 0.790. In the soil seed bank of Area_B (forest being restored only by planting seedlings), 1,623 individuals (721.3 individuals $m^{-2}$), belonging to 42 species and 18 botanical families, were recorded, with (H') = 2.768 and (J') = 0.741 (Table 3).

**Table 3 -** Floristics and phytosociology of the soil seed bank species of the forests undergoing restoration (Area_A = planting of native tree species and nucleation techniques and Area_B = planting of native tree species).

| **Botanical family/ Species** | **Area A** | **NI** | **RelDe (%)** | **RelFr (%)** | **Area B** | **NI** | **RelDe (%)** | **RelFr (%)** | **DS** | **SC** | **LF** | **C** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Amaranthaceae** | | | | | | | | | | | | |
| *Alternanthera tenella* Colla | | 9 | 0,76 | 1,63 | | | | | Zoo | P | H | N |
| *Amaranthus deflexus* L. | | 45 | 3,82 | 0,65 | . | 13 | 0,8 | 0,97 | Zoo | P | H | E |
| *Amaranthus spinosus* L. | | 1 | 0,08 | 0,33 | | | | | Zoo | P | H | E |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Asteraceae** | | | | | | | | | | | | |
| *Acanthospermum australe* (Loefl.) Kuntze | . | 116 | 9,85 | 8,5 | . | 125 | 7,7 | 8,41 | Zoo | P | H | N |
| *Ageratum conyzoides* L. | . | 19 | 1,61 | 2,61 | . | 33 | 2,03 | 3,24 | Zoo | P | H | N |
| *Baccharis dracunculifolia* DC. | . | 17 | 1,44 | 3,27 | . | 60 | 3,7 | 4,53 | Ane | P | S | N |
| *Baccharis trimera* (Less.) DC. | . | 1 | 0,08 | 0,33 | . | 1 | 0,06 | 0,32 | Ane | P | H | N |
| *Bidens pilosa* L. | . | 8 | 0,68 | 1,63 | . | 4 | 0,25 | 0,65 | Zoo | P | H | N |
| *Conyza bonariensis* (L.) Cronquist | . | 183 | 15,53 | 8,17 | . | 113 | 6,96 | 7,12 | Ane | P | H | N |
| *Eclipta alba* (L.) Hassk | . | 13 | 1,1 | 1,63 | . | 44 | 2,71 | 2,91 | Ane | ES | H | N |
| *Erechtites hieraciifolius* (L.) Raf. Ex DC. | | | | | . | 4 | 0,25 | 0,97 | Ane | P | H | N |
| *Erechtites valerianifolius* (Wolf) DC. | . | 1 | 0,08 | 0,33 | . | 7 | 0,43 | 0,97 | Ane | P | H | N |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Eupatorium laevigatum* Lam. | | | | | . | 4 | 0,25 | 0,32 | Ane | P | S | N |
| *Gnaphalium pensylvanicum* Wild. | . | 18 | 1,53 | 2,29 | . | 16 | 0,99 | 1,62 | Ane | ES | H | N |
| *Gnaphalium purpureum* L. | . | 27 | 2,29 | 4,58 | . | 55 | 3,39 | 4,85 | Ane | ES | H | N |
| *Gnaphalium spicatum* Lam. | . | 3 | 0,25 | 0,65 | | | | | Ane | ES | H | N |
| *Mikania hirsutissima* DC. | . | 1 | 0,08 | 0,33 | . | 3 | 0,18 | 0,97 | Ane | Nc | V | N |
| *Pluchea sagittalis* Lam. | | | | | . | 3 | 0,18 | 0,97 | Ane | P | H | N |
| *Porophyllum ruderale* (Jacq.) Cass. | . | 9 | 0,76 | 1,96 | . | 11 | 0,68 | 2,27 | Ane | P | H | N |
| *Sonchus oleraceus* L. | . | 42 | 3,57 | 5,23 | . | 58 | 3,57 | 5,18 | Ane | P | H | N |
| *Vernonanthura phosphorica* (Vell.) H.Rob. | . | 63 | 5,35 | 6,21 | . | 39 | 2,4 | 4,21 | Ane | P | T | N |
| **Begoniaceae** | | | | | | | | | | | | |
| *Begonia cucullata* Willd. | . | 1 | 0,08 | 0,33 | . | 1 | 0,06 | 0,32 | Ane | P | H | N |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Begonia* sp. | | | | | . | 1 | 0,06 | 0,32 | Ane | P | H | N |
| **Brassicaceae** | | | | | | | | | | | | |
| *Lepidium virginicum* L. | . | 24 | 2,04 | 4,58 | . | 16 | 0,99 | 2,91 | Aut | P | H | E |
| **Cannabaceae** | | | | | | | | | | | | |
| *Trema micrantha* (L.) Blume | | 7 | 0,59 | 0,65 | . | 16 | 0,99 | 1,29 | Zoo | P | T | N |
| **Convolvulaceae** | | | | | | | | | | | | |
| *Ipomoea triloba* L. | . | 1 | 0,08 | 0,33 | . | 2 | 0,12 | 0,32 | Aut | P | V | N |
| **Euphorbiaceae** | | | | | | | | | | | | |
| *Chamaesyce hirta* (L.) Millsp. | . | 31 | 2,63 | 4,9 | . | 25 | 1,54 | 3,56 | Aut | P | H | N |
| *Chamaesyce hyssopifolia* (L.) Small | . | 75 | 6,37 | 4,9 | . | 85 | 5,24 | 4,21 | Aut | P | H | N |
| *Croton glandulosus* L. | . | 5 | 0,42 | 0,65 | . | 1 | 0,06 | 0,32 | Zoo | P | S | N |
| **Fabaceae** | | | | | | | | | | | | |
| *Cajanus cajan* (L.) Millsp. | . | 4 | 0,34 | 1,31 | . | 3 | 0,18 | 0,97 | Aut | P | S | E |
| *Crotalaria juncea* L. | . | 4 | 0,34 | 0,98 | . | 3 | 0,18 | 0,97 | Aut | P | S | E |
| *Desmodium barbatum* L. Benth | . | 41 | 3,48 | 3,92 | . | 101 | 6,22 | 6,15 | Zoo | P | H | N |
| *Glycine wightii* Verdc. | . | 1 | 0,08 | 0,33 | . | 3 | 0,18 | 0,65 | Nc | P | V | E |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Senegalia polyphylla* (DC.) Britton & Rose. | . | 1 | 0,08 | 0,33 | | | | | Aut | ES | T | N |
| **Lamiaceae** | | | | | | | | | | | | |
| *Hyptis suaveolens* (L.) Point | . | 97 | 8,23 | 3,27 | . | 128 | 7,89 | 3,24 | Zoo | P | H | N |
| **Lythraceae** | | | | | | | | | | | | |
| *Cuphea elliptica* Koehne | . | 122 | 10,36 | 3,59 | . | 8 | 0,49 | 1,62 | Aut | Nc | S | E |
| **Malvaceae** | | | | | | | | | | | | |
| *Sida rhombifolia* L. | . | 10 | 0,85 | 1,96 | . | 1 | 0,06 | 0,32 | Zoo | ES | H | N |
| **Melastomaceae** | | | | | | | | | | | | |
| *Clidemia hirta* (L.) | . | 8 | 0,68 | 1,96 | . | 11 | 0,68 | 2,59 | Zoo | ES | S | N |
| *Tibouchina granulosa* (Desr.) Cogn | . | 5 | 0,42 | 0,65 | | | | | Zoo | P | T | N |
| **Onagraceae** | | | | | | | | | | | | |
| *Ludwigia tomentosa* (Cambess.) | . | 60 | 5,09 | 3,27 | . | 430 | 26,49 | 6,8 | Ane | P | S | N |
| **Oxalidaceae** | | | | | | | | | | | | |
| *Oxalis curniculata* L. | . | 8 | 0,68 | 2,61 | . | 45 | 2,77 | 4,53 | Aut | P | H | N |
| **Phyllantaceae** | | | | | | | | | | | | |
| *Phyllanthus tenellus* Roxb. | . | 9 | 0,76 | 1,31 | . | 7 | 0,43 | 0,65 | Aut | ES | H | N |
| **Plantaginaceae** | | | | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Scoparia dulcis* L. | . | 1 | 0,08 | 0,33 | | | | | Aut | P | H | N |
| *Stemodia verticillata* Mill. | . | 1 | 0,08 | 0,33 | . | 22 | 1,36 | 1,29 | Aut | P | H | N |
| **Rosaceae** | | | | | | | | | | | | |
| *Rubus rosifolius* Sm. | . | 9 | 0,76 | 0,65 | | | | | Zoo | LS | S | N |
| **Rubiaceae** | | | | | | | | | | | | |
| *Spermacoce capitata* Ruiz & Pav. | | | | | . | 1 | 0,06 | 0,32 | Aut | ES | H | N |
| *Spermacoce latifolia* Aubl. | | | | | . | 1 | 0,06 | 0,32 | Aut | ES | H | N |
| **Solanaceae** | | | | | | | | | | | | |
| *Physalis angulata* L. | . | 1 | 0,08 | 0,33 | | | | | Zoo | P | H | N |
| *Solanum americanum* Mill. | . | 76 | 6,45 | 6,21 | . | 115 | 7,09 | 5,5 | Zoo | P | H | N |
| *Solanum paniculatum* L. | | | | | . | 4 | 0,25 | 0,32 | Zoo | P | T | N |
| **TOTAL** | | **1178** | **100** | **100** | | **1623** | **100** | **100** | | | | |

NI: Number of individuals; RelDel: Relative density; RelFr: Relative frequency; DS: Dispersal syndrome (Ane= anemochory; Zoo= zoochory; Aut= autochory); SC: Successional category (P= Pioneer, ES= Early secondary, LS= Late secondary); LF: Life Form; (T= Tree, S= Shrub, H= Herb, V= Vine); OR: Origin (N= Native, E= Exotic); Nc: Not Classified; *: Indicates de presence of the species in the soil seed bank

**Species diversity: the three Hill numbers**

The pattern of species diversity showed marked differences between numbers Hill´s, presenting the following order q2 < q1 < q0. However, analyzing between the areas no differences were observed according to the species richness index (q=0), Shannon diversity (q=1) and Simpson diversity (q = 2). For both the rarefaction and extrapolation curves the overlapping of confidence intervals indicates that there are no differences between areas (Figure 2).

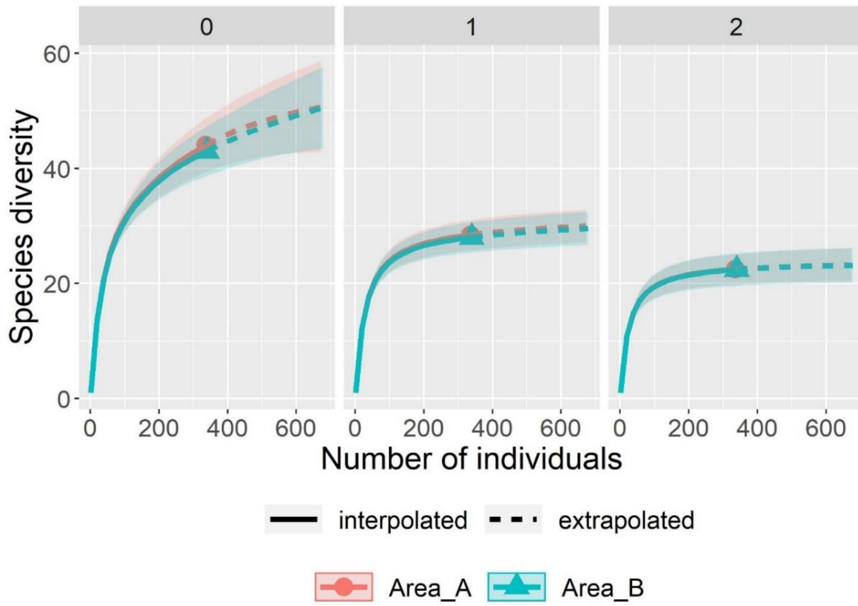



**Figure 2.** Rarefaction (solid line) and extrapolation (dashed lines) curves of species richness in Hill numbers (q = 0,1,2), based on the number of individuals from two areas under restoration (Area_A and Area_B). The rarefaction and extrapolation curves show the lines representing the mean values and the standard deviation bands with 95% confidence intervals.

There were no significant differences when comparing the mean species richness (p-value 0.9025) between the studied areas (Area_A: 10.2 and Area_B: 10.3). The same behavior was observed in relation to the abundance of individuals (p-value 0.08099) with Area_A with an average of 39.27 individuals per plot and Area_B with an average of 54.10 individuals (Figure 3).

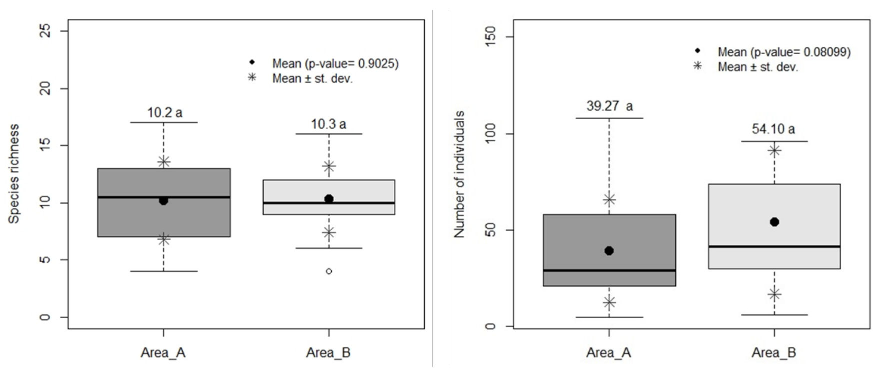



**Figure 3.** Boxplot of a) species richness and b) individual abundance. Numbers followed by equal letters are statistically equal p [?] 0.05 (Tukey's t test). st. dev = standard deviation).

**Floristic composition**

Considering both areas, 2,801 seedlings germinated in the soil seed banks, 50 species and 19 botanical families were recorded. Of this set, 8 species were exclusive to Area_A, 7 species found only in Area_B and 35 species were common in both areas. In the NMDS analysis, the two areas overlapped, with small statistical differences (Permanova: $F_{1,57} = 1,68$; $P = 0.0255$), indicating similarity in species composition between the areas (Figure 4).

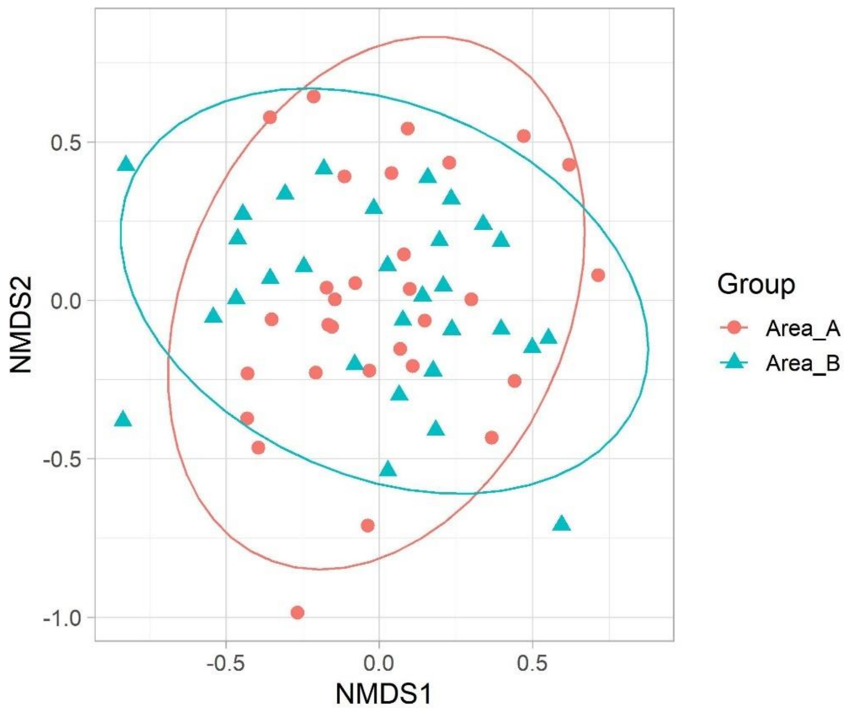



**Figure 4.** Non-Metric Multidimensional Scaling (NMDS) for the floristic composition of soil seed banks from two adjacent areas (Area_A and Area_B), submitted to different ecological restoration techniques.

In Area_A, the families Asteraceae (44.23%), Lythraceae (10.36%), Euphorbiaceae (9.42%), Lamiaceae (8.23%) and Solanaceae (6.54%) had the highest relative densities, making a total of 78.78% of germinated individuals. The families with the highest species richness were Asteraceae (15 species), Fabaceae (5), Euphorbiaceae (3) and Amaranthaceae (3). In Area_B, the families Asteraceae (35.74%), Onagraceae (26.49%), Lamiaceae (7.89%), Solanaceae (7.33%) and Euphorbiaceae (6.84%) were predominant in terms of relative density, representing together 84.29% of germinated individuals. Regarding species richness, the families Asteraceae (17 species) and Euphorbiaceae (3) stood out.

**Functional groups**

As for the functional attributes, in both seed banks there was a predominance of species and individuals with the herbaceous life form and native origin. In addition, 76 tree species were found in Area_A, being *Vernonanthura phosphorica* (Vell.) H.Rob. (63 individuals),*Trema micrantha* (L.) Blume (7), *Tibouchina granulosa*(Desr.) Cogn (5), *Senegalia polyphylla* (DC.) Britton & Rose. (1). In Area_B, 59 tree species were recorded, being*Vernonanthura phosphorica* (39), *Trema micrantha* (16) and*Solanum paniculatum* L. (4).

The classification in successional categories showed the predominance of the pioneer category (P), both at the species level (Area_A = 74.42%; Area_B= 76.19%), and at the level of individuals (Area_A = 81.24%; Area_B = 90.94%), in both areas. In Area_A, the presence of*Rubus rosifolius* Sm., a late secondary species that presents zoochoric dispersion, stands out.

Regarding the dispersion syndrome, in Area_A there was a predominance of the zoochorous category, in relation to the number of species: zoochorous (37.21%), followed by anemochoric (32.56%) and autochoric (27.91%) species. The same behavior was observed in relation to the number of individuals, zoochoric (38.79%), anemochoric (37.27%) and autochoric (23.85%). In Area_B, it was observed that 40.48% of the species were classified as anemochoric, 28.57% autochoric and 28.57% zoochoric. As for the number of individuals, anemochoric (52.37%), zoochoric (34.01%) and autochoric (13.43%).

The rarefaction and extrapolation curves based on the species composition of different dispersion syndromes show small differences in species richness. Although their confidence intervals overlapped, it is possible to notice that in Area_A there is a predominance of zoochoric species/individuals, while in Area_B there is a predominance of anemochoric species/individuals (Figure 5).

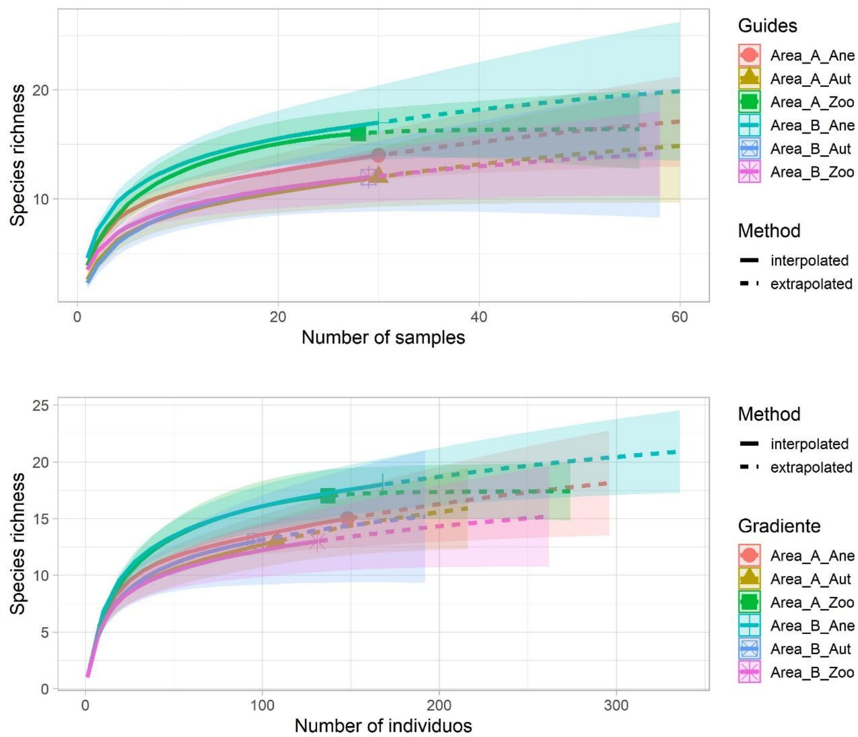



**Figure 5.** Sample-based rarefaction curves and individual-based rarefaction curves based on species composition from different dispersal syndrome. (Ane = anemochoric; Aut = autochoric; Zoo = zoochoric).

Although their confidence intervals overlap slightly, sample-based rarefaction curves and individual-based rarefaction curves demonstrate that zoochorous species are prominent in Area_A (Figure 6).

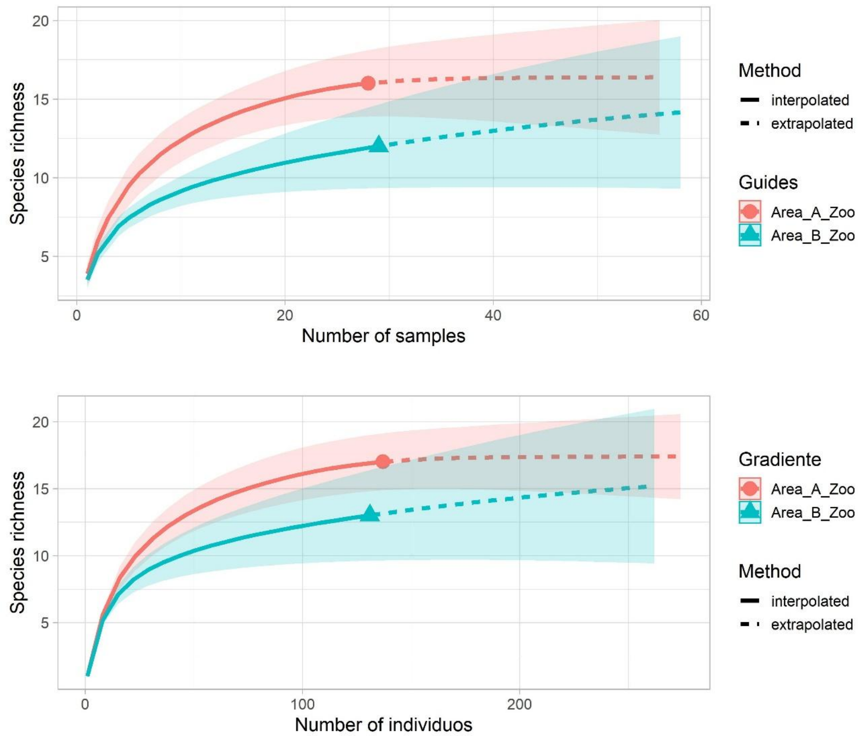



**Figure 6.** Sample-based rarefaction curves and individual-based rarefaction curves based on species composition with zoochoric dispersal syndrome.

### Floristic similarity patterns

The results demonstrate high floristic similarity between the plots of the two areas (Figure 7). For example, adopting a cut-off point of 80% floristic similarity, there is a tendency to group plots located in the same area as 4, 19, 21 and 23 belonging to Area_A and in plots 31, 33, 34 and 38 belonging to Area_B. The analysis of the bidirectional dendrogram indicated that the vegetation of the study areas could be divided into five groups, with arrangements and groupings influenced by the functional attributes of the species and the restoration techniques implemented in each area.

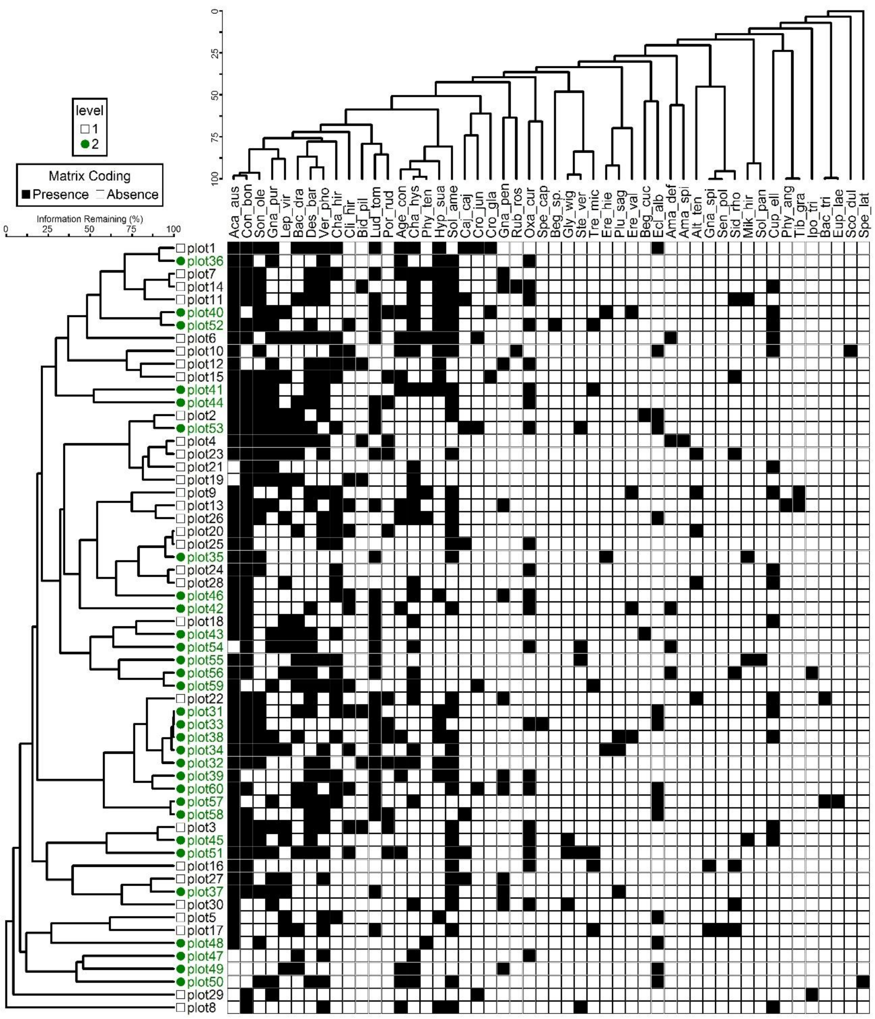



**Figure 7.** Bidirectional cluster dendrogram generated based on the Bray-Curtis dissimilarity index, showing the distribution of 50 species in two areas in the bauxite mining environment and 60 plots in Miraí-MG, Brazil. level 1: Area_A; level 2: Area_B

## DISCUSSION

The results of this study showed that the soil seed banks, from both areas, presented viable seeds and are composed mostly of pioneer and native seeds, that is, it is an important indicator of the recovery potential of plant communities through the natural regeneration. This pattern is common in early successional stage forests (Miranda-Neto et al., 2016; Balestrin et al., 2019; Martins et al., 2021). For example, the soil seed bank in tropical regions is mainly composed of pioneer species, light-demanding and has a higher density of seeds in the surface layers of the soil (Martins et al., 2015; Silva et al., 2021a; Martins et al., 2021). Several studies report the importance of seeds of pioneer species stored in the soil and their role in the formation of a persistent bank, due to high seed production, efficient dispersal mechanisms, long seed viability and rapid growth (Kunz & Martins 2016; Balestrin et al., 2019; Silva et al., 2019; Miranda-Neto et al., 2021; Martins et al., 2021; Silva et al., 2021a; Adjalla et al., 2022). However, for the results show that the floristic composition, the Shannon diversity indices (Area_A: H' = 2.970 and Area_B: H' = 2.768) indicating higher diversity and the Pielou equabilities (Area_A: J' = 0.790 and Area_B: J' = 0.741) indicate floristic heterogeneity in both areas. These results corroborate those observed by Balestrin et al. (2019) and Martins et al. (2021) in the same region and in areas in the bauxite mining environment. The superiority of the diversity values (H' and J') observed in Area_A, in relation to Area_B, is probably related to the nucleation techniques complementary to the planting of seedlings, which promotes a higher species richness and composition.

The soil seed bank of both areas under restoration showed higher density of herbaceous individuals and richness of herbaceous species. This result corroborates studies carried out in areas undergoing secondary succession in the tropical forest (Miranda-Neto 2014b;2016; Silva et al., 2019; Balestrin et al., 2019; Silva et al., 2021a; Martins et al., 2021; Silva et al., 2021b; Adjalla et al., 2022). These results suppose that the dominance of the herbaceous life form is related to the short life cycle of these species, high seed production and environmental conditions after disturbance, such as higher luminosity due to the lower plant coverage. Thus, herbaceous plants are essential for the fast colonization a plant coverage recovery, which can stabilize soil aggregates and improve water retention and attenuate erosion processes during early successional stages (Martins et al., 2021). Furthermore, the absence of invasive exotic grasses can be a suitable indicator of the soil seed banks quality, since as the successional process advances, there will be an increase in shrub and tree species, and consequently higher canopy cover which can reduce the herbaceous species density in the soil seed bank (Balestrin et al., 2019; Silva et al., 2021b; Martins et al., 2021).

The novelty of this investigation was to observe how different restoration techniques influence the functional composition of the soil seed bank. Considering the initial situation of the soil in both areas (exposed and compacted subsoil) it is possible to suppose that most of the seeds from the soil seed bank were lost in the soil stabilization process (earthwork) for the construction of the mining company's administrative structures. Furthermore, the similarities in edaphic conditions (relief, fertility, soil preparation) between the study areas (Area_A and Area_B) may explain the few differences found in terms of floristic composition. The floristic results of this research reflect the contributions of the implemented restoration techniques, such as: Seeds from soil transposition, direct sowing and green manuring; Propagules dispersed by planted trees and the attraction of seed-dispersing fauna by zoochoric species (Viani et al., 2015; Silva et al., 2015; Corlett 2017; Aslan et al., 2019; Fonseca & Martins, 2021). Seeds can be deposited at different depths in the soil, depending on the quantity, weight and size of the seeds, however, several studies indicate a higher density of seeds in the surface layers of the soil (Martins 2015; Miranda-Neto et al 2016; Menezes et al 2019; Balestrin et al., 2019; Silva et al., 2021a; Martins et al., 2021). In this sense, understanding the relationship between the soil seed bank and seed dispersal is critical to understanding the establishment of plant populations and community dynamics (Aslan et al., 2019).

In Area_A (restoration by planting seedlings and nucleation techniques) there was a predominance of zoochoric species and individuals. On the other hand, in Area_B (restoration by planting seedlings only), anemochoric species and individuals were predominant. The differences observed regarding the functional composition of the species between the areas showed that the nucleation techniques (soil transposition and direct seeding) contributed to the increase in the diversity of zoochoric species in the area and can be used as complementary techniques for enrichment in projects of forest compensatory restoration in pasture areas and areas in the bauxite mining environment (Martins 2018; Martins et al., 2020; Onésimo et al., 2021; Fonseca 2021). Zoochoric species in the soil seed bank are essential for attracting and maintaining propagule-dispersing fauna, and thus can contribute to increasing ecological interactions in the area under restoration (Silva et al., 2016; Corlett 2017; Martins et al., 2021; Fonseca 2021) and for increased regeneration in early stages, as indicated by studies conducted in the Atlantic Forest (Viani et al., 2015; Camargo et al., 2020). Thus, seed dispersal is key to maintaining biodiversity (Corlett 2017), especially in tropical regions, where 50-90% of tree species are dispersed by animals (Sarmento et al., 2021).

The restoration techniques used were also efficient to improve soil chemical parameters, mainly in terms of total-N, soil organic matter and base saturation. In Area_A, there was an increase of 2080% in MO levels, 868% in total-N and 133% in base saturation (V%), while in Area_B there was an increase of 760% in MO, 600% in total-N contents and 94% in base saturation. The superiority of the values observed in Area_A is probably related to the transposition of topsoil, since the litter is the main route of transfer in the flow of nutrients, provides improvement in soil fertility and contributes to the sustainability of the forest (Silva et al., 2015).

Although the two plant communities analyzed in this study (Area_A and Area_B) show similar species richness pattern, differences in species dominance and uniformity were observed, which can directly influence the plant assembly community, natural succession and ecological restoration (Chao et al. 2014, Mori et al., 2018; Adjalla et al., 2022). The dendrogram analysis is a key information for the biodiversity conservation that highlights the relative importance of groups (dispersion syndrome and successional category) and their ecosystem services and ecological functionality (Aslan et al., 2019; Akcakaya et al., 2020; Larson & Suding, 2022). These clusters occur because many zoochorous species may be dispersed under nests or along routes used by birds and frugivorous animals (Corlett 2017; Martins et al., 2021). In addition, the early successional groups (pioneers and early secondaries) corroborates that remain dormant in the seed bank, (Balestrin et al., 2019). Thus, evaluating functional identity and trait composition should be a premise to select species during tropical forest restoration (Campanharo et al., 2021). For example, specifically, autochoric dispersal and nitrogen-fixing trees species as biomass dominant groups have an important role during forest restoration on mining tailings (Campanharo et al., 2021). These groups can be an indicator to the context-dependent conditions of each study area (i.e., edaphic conditions, luminosity, soil fertility) and mainly to the restoration techniques implemented in each area.

Thus, the evaluation and monitoring of the soil seed bank is essential to understand the changes that occur along the secondary succession in tropical forests. In this context, trait-based approaches allow a better understanding of the forest biodiversity and ecosystem biodiversity recovery (Sarmento et al., 2021; Campanharo et al., 2021). Thus, knowledge the patterns of biodiversity in the soil seed bank is essential for land use planning, for defining conservation and restoration policies and for choosing the most appropriate techniques in different mining sceneries (Martins 2018; Martins et al., 2020; Martins et al., 2021; Fonseca 2021; Larson & Suding, 2022). Thus, it is observed that in early stages, restoration techniques positively influence the functional composition of the seed bank species. In addition, nucleation as a complementary technique contributed to increasing the species richness dispersed by animals, which can accelerate the forest recovery. Thus, the functional characterization of soil seed banks and their relationship with different restoration techniques can provide essential information on the ecological mechanisms that guide successional dynamics.

## CONCLUSIONS

The soil seed banks of the two studied areas are floristically relatively similar (pioneer species and individuals, herbaceous and of native origin were the dominant groups), showing higher potential for natural regeneration. However, the greater species richness and abundance of zoochoric individuals in Area_A demonstrates that nucleation techniques, such as topsoil transposition and direct seeding are suitable and fast to biodiversity recovery.

In early successional stages, restoration techniques are more determinant in the functional composition than in the floristic composition of the soil seed bank. The knowledge of the diversity pattern and the functional groups (successional category and dispersion syndrome) of the soil seed bank provides information on the mechanisms that guide the successional dynamics and is fundamental for the evaluation and monitoring of areas in the environment of bauxite mining. The forest restoration techniques applied in both areas have promoted rapid forest cover.

## ACKNOWLEDGMENTS

The authors thank the Coordenacao de Aperfeicoamento de Pessoal de Nivel Superior (CAPES) and Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq) by research fellowships for the authors and to the Companhia Brasileira de Aluminio for provided infrastructure and financial support for the project.

## REFERENCIAS

Adjalla, C., Tosso, F., Salako, K. V., & Assogbadjo, A. E. (2022). Soil seed bank characteristics along a gradient of past human disturbances in a tropical semi-deciduous forest: Insights for forest management. *Forest*

*Ecology and Management*, 503, 119744.*https://doi.org/10.1016/j.foreco.2021.119744*

Akcakaya, H. R., Rodrigues, A. S., Keith, D. A., Milner-Gulland, E. J., Sanderson, E. W., Hedges, S., ... & Stephenson, P. J. (2020). Assessing ecological function in the context of species recovery. *Conservation Biology*, *34* (3), 561-571.*https://doi.org/10.1111/cobi.13425*

Aslan, C., Beckman, N. G., Rogers, H. S., Bronstein, J., Zurell, D., Hartig, F., ... & Zhou, Y. (2019). Employing plant functional groups to advance seed dispersal ecology and conservation. *AoB Plants*, *11* (2), plz006.*https://doi.org/10.1093/aobpla/plz006*

Balestrin, D., Martins, S. V., Schoorl, J. M., & Lopes, A. T. (2018). Modelagem do processo erosivo e deposicao de sedimentos sob diferentes cenarios e usos do solo em uma area com perfil minerario em Minas Gerais-Brasil. In: Correia C.M.C, Melo M.C, Santos N.A.P (Org.). Compartilhando experiencias das aguas de Minas Gerais - Brasil. 1 ed. Vol 1. Belo Horizonte: Instituto Mineiro de Gestao das Aguas, 101-104.

Balestrin, D., Martins, S. V., Fonseca, W. S., & Cosimo, L. H. E. (2019). Relationship between soil seed bank and canopy coverage in a mined area. *Revista Arvore*, *43* (4): e430403.*https://doi.org/10.1590/1806-908820190004000003*

Bizuti, D. T., Robin, A., Soares, T. M., Moreno, V. S., Almeida, D. R., Andreote, F. D., ... & Brancalion, P. H. (2022). Multifunctional soil recovery during the restoration of Brazil's Atlantic Forest after bauxite mining. *Journal of Applied Ecology*.*https://doi.org/10.1111/1365-2664.14097*

Borges, S. R., Santos, R. S., Oliveira, D. M., Souza, I. F., Verburg, E. E., Pimentel, L. G., ... & Silva, I. R. (2019). Practices for rehabilitating bauxite-mined areas and an integrative approach to monitor soil quality. *Land Degradation & Development*,*30* (7), 866-877.*https://doi.org/10.1002/ldr.3273*

Camargo, P. H., Pizo, M. A., Brancalion, P. H, & Carlo, T. A. (2020). Fruit traits of pioneer trees structure seed dispersal across distances on tropical deforested landscapes: Implications for restoration.*Journal of Applied Ecology*, *57* (12), 2329-2339.*https://doi.org/10.1111/1365-2664.13697*

Campanharo, I. F, Martins, S. V., Villa, P. M., Kruschewsky, G. C, Dias, A. A & Nabeta F. H (2021). Functional composition enhances aboveground biomass stock undergoing active forest restoration on mining tailings in Mariana, Brazil. *Restoration Ecology*, 29(5), e13399.*https://doi.org/10.1111/rec.13399*

Chao, A., Gotelli, N. J., Hsieh, T. C., Sander, E. L., Ma, K. H., Colwell, R. K., & Ellison, A. M., (2014). Rarefaction and extrapolation with Hill numbers: A framework for sampling and estimation in species diversity studies. *Ecological Monographs*. 84, 45–67.*https://doi.org/10.1890/13-0133.1*

Carlucci, M. B., Brancalion, P. H., Rodrigues, R. R., Loyola, R., & Cianciaruso, M. V. (2020). Functional traits and ecosystem services in ecological restoration. *Restoration Ecology*, *28* (6), 1372-1383.*https://doi.org/10.1111/rec.13279*

Coelho, A. J. P., Villa, P. M., Matos, F. A. R., Heringer, G., Bueno, M. L., de Paula Almado, R., & Meira-Neto, J. A. A. (2022). Atlantic Forest recovery after long-term eucalyptus plantations: The role of zoochoric and shade-tolerant tree species on carbon stock. *Forest Ecology and Management*, *503*, 119789.*https://doi.org/10.1016/j.foreco.2021.119789*

Corlett, R. T. (2017). Frugivory and seed dispersal by vertebrates in tropical and subtropical Asia: an update. *Global Ecology and Conservation*, 11, 1-22.*https://doi.org/10.1016/j.gecco.2017.04.007*

Crawley, M. J (2013). *The R book: Second Edition*. John Wiley and Sons Ltd, West Sussex, United Kingdom, p 975

Crouzeilles, R., Ferreira, M. S., Chazdon, R. L., Lindenmayer, D. B., Sansevero, J. B., Monteiro, L., ... & Strassburg BB. (2017). Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. *Science advances*, 3(11), e1701345.*https://www.science.org/doi/10.1126/sciadv.1701345*

Diniz, E. S & Villa, P. M. (2020). *Aplicacoes da Linguagem R em Analises de Vegetacao* . 1ed.Ponta Grossa, PR: Atena Editora, 2020, v.1.

IBRAM. (2022). *Praticas em Circularidade no Setor Mineral - E Book* . In Rodrigues CP, Dias CFS, Malheiros C. (Org.). 1.ed. Brasilia: Instituto Brasileiro de Mineracao.

IBGE. (2012). *Manual Tecnico da Vegetacao Brasileira* . 2nd ed. Manuais Tecnicos em Geociencias. Rio de Janeiro, Brasil: Instituto Brasileiro de Geografia e Estatistica.

Fonseca, W. S. (2021). Bioindicadores para avaliacao e monitoramento da restauracao ecologica de area em ambiente de mineracao de bauxita, Mirai, MG. In *Dissertacao (Mestrado em Ciencia Florestal).*Vicosa, Brasil: Universidade Federal de Vicosa.*https://locus.ufv.br//handle/123456789/28543*

Fonseca, W. S, & Martins, S. V. (2021). Monitoramento de fauna como indicador de restauracao florestal de uma area em ambiente de mineracao de bauxita na Zona da Mata Mineira. In Oliveira, R.J (Ed.). *Aguas e Florestas: Desafios Para Conservacao e Utilizacao* (pp. 340-357). Guaruja, Sao Paulo: Editora Cientifica Digital.*https://dx.doi.org/10.37885/210404406*

Fonseca, W. S., Martins, S. V., & Villa, P. M. (2023). Green Manure as an Alternative for Soil Recovery in a Bauxite Mining Environment in Southeast Brazil. Floresta e Ambiente, 30(1), 1-14.*https://doi.org/10.1590/2179-8087-FLORAM-2023-0041*

Holl, K. D. (2017). Research directions in tropical forest restoration. Annual Missouri Botanical Garden 102:237–250.*https://doi.org/10.3417/2016036*

Hsieh, T. C., Ma, K. H., & Chao, A. (2016). iNEXT: an R package for rarefaction and extrapolation of species diversity (H ill numbers).*Methods in Ecology and Evolution* , 7(12), 1451-1456.*https://doi.org/10.1111/2041-210X.12613*

Jakovac, C. C., Meave, J. A., Bongers, F., Letcher, S. G., Dupuy, J. M., Piotto, D., ... & Poorter, L. (2022). Strong floristic distinctiveness across Neotropical successional forests. *Science Advances* , 8(26), eabn1767.*https://www.science.org/doi/10.1126/sciadv.abn1767*

Jost, L. (2006). *Entropy and diversity* . *Oikos* ,*113* (2), 363–375.*https://doi.org/10.1111/j.2006.0030-1299.14714.x*

Jost, L. (2007). Partitioning diversity into independent alpha and beta components. *Ecology* , *88* (10), 2427–2439.*https://doi.org/10.1890/06-1736.1*

Koppen, W. (1948). *Climatologia: con un estudio de los climas de la tierra.* Mexico: Fondo de Cultura Economica.

Kunz, S. H, & Martins, S. V. (2016). Soil seed bank in seasonal semideciduous forest and abandoned pasture. *Revista Arvore,* 40(6), 991-1001.*https://doi.org/10.1590/0100-67622016000600004*

Larson, J. E., & Suding, K. N. (2022). Seed bank bias: Differential tracking of functional traits in the seed bank and vegetation across a gradient. *Ecology* , *103* (4), e3651.*https://doi.org/10.1002/ecy.3651*

Lewis, S. L., Edwards, D. P., & Galbraith, D. (2015). Increasing human dominance of tropical forests. *Science* , *349* (6250), 827-832.*https://www.science.org/doi/10.1126/science.aaa9932*

Lima, R. A., Oliveira, A. A., Pitta, G. R., de Gasper, A. L., Vibrans, A. C., Chave, J., ... & Prado, P. I. (2020). The erosion of biodiversity and biomass in the Atlantic Forest biodiversity hotspot. *Nature communications* , *11* (1), 1-16.*https://doi.org/10.1038/s41467-020-20217-w*

Londe, V., Farah, F. T., Rodrigues, R. R., & Martins, F. R. (2020). Reference and comparison values for ecological indicators in assessing restoration areas in the Atlantic Forest. *Ecological Indicators* , 110, 105928.*https://doi.org/10.1016/j.ecolind.2019.105928*

Martins, S. V., Borges, E. E. L., & Silva, K. A. (2015). O banco de sementes do solo e sua utilizacao como bioindicador de restauracao ecologica. In S. V. Martins (Ed.), *Restauracao ecologica de ecossistemas degradados* (2nd ed., pp. 293-330). Vicosa, Brasil: Editora UFV.

Martins, S.V. (2018). Alternative Forest Restoration Techniques. In: Viana H, (Ed.). *New Perspectives in Forest Science* . 1st ed. London: IntechOpen: 131-148.

Martins, S. V., Cosimo, L. H. E., Balestrin, D., Fonseca, W. S., Andrade, C. F., & Barros, R. S. (2020). Restoration of Tree and Shrub Diversity Post Bauxite Mining, in the Southeastern Region of Minas Gerais, Brazil. In: Kristian de Vlieger. (Org.). *Recent Advances in Ecological Restoration v.1* (pp. 33-62). 1ed. Estados Unidos: Nova

Martins, S. V., Fonseca, W. S., Cosimo, L. H. E., & Balestrin, D. (2021). Soil Seed Banks in Two Environments of Forest Restoration Post Bauxite Mining: Native Tree Plantation and Natural Regeneration.*Research in Ecology* , 3, 15-25.*https://doi.org/10.30564/re.v3i1.2631*

Martins, S. V., Fonseca, W. S., Andrade, C. F., Barros, R. S., Paiva, J. M., Silva, C. H. & Brito, M. A. F. (2022). Reflorestamento com mudas altas: uma inovacao da restauracao florestal na mineracao de bauxita em Minas Gerais. In: Oliveira, R.J, (Ed.). *Engenharia florestal: contribuicoes, analises e praticas em pesquisa* . Guaruja: Editora Cientifica Digital; 2022.*https://doi.org/10.37885/220308108*

Miranda-Neto, A., Martins, S. V., Silva, K. D. A., Lopes, A. T, & Demolinari, R (2014a). 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>.

Miranda-Neto, A., Martins, S. V., Silva, K. D. A., & Gleriani, J. M. (2014b). Banco de sementes do solo e serapilheira acumulada em floresta restaurada. *Revista Arvore* , 38(4)*,* 609-620. *https://doi.org/10.1590/S0100-67622014000400004*

Miranda-Neto, A., Martins, S. V., Silva, K. D. A., Lopes, A. T., & Demolinari, R. D. A. (2016). Banco de sementes em mina de bauxita restaurada no Sudeste do Brasil. *Floresta e Ambiente* , *24* , e00125414.*https://doi.org/10.1590/2179-8087.125414*

Miranda-Neto, A., Martins, S. V., & Silva, K. A. (2021). Soil seed banks in different environments: initial forest, mature forest, Pinus and Eucalyptus abandoned stands. *Plant Biosystems* , 155(1), 128-135.*https://doi.org/10.1080/11263504.2020.1727979*

Mori, A. S., Isbell, F., & Seidl, R. (2018). β-diversity, community assembly, and ecosystem functioning. *Trends in ecology & evolution* , *33* (7), 549-564.*https://doi.org/10.1016/j.tree.2018.04.012*

Mueller–Dombois D & Ellenberg H. (1974). *Aims and methods of vegetation ecology* . New York: John Wiley & Sons.

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, & E., Wagner, E. (2018) 'Vegan': community ecology package. R package version 2.4-6.*https://cran.r-project.org/web/packages/vegan/vegan.pdf.*[Accessed 5 May 2022]

Onésimo, C. M., Dias, D. D., Vale Beirão, M., Kozovits, A. R., & Messias, M. C. T. (2021). Ecological succession in areas degraded by bauxite mining indicates successful use of topsoil. Restoration Ecology, 29(1), e13303.*https://doi.org/10.1111/rec.13303*

Poorter, L., Rozendaal, D., Bongers, F., de Almeida-Cortez, J. S., Almeyda Zambrano, A. M., Álvarez, F. S., . . . & Westoby, M. (2019). Wet and dry tropical forests show opposite successional pathways in wood density but converge over time. Nature ecology & evolution, 3(6), 928-934.*https://doi.org/10.1038/s41559-019-0882-6*

R-Core Team. (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org. [accessed 01 may 2022].

Rezende, C. L., Scarano, F. R., Assad, E. D., Joly, C. A., Metzger, J. P., Strassburg, B. B. N., . . . & Mittermeier, R. A. (2018). From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. *Perspectives in ecology and conservation* , *16* (4), 208-214.*https://doi.org/10.1016/j.pecon.2018.10.002*

Ribeiro, A. C., Guimarães, P. T. G., & Alvarez, V. H. V. (1999).*Recomendações para o uso de corretivos e fertilizantes em Minas Gerais - 5ª Aproximação* . Viçosa, MG: Comissão de Fertilidade do Solo do Estado de Minas Gerais.

Romanelli, J. P., Meli, P., Santos, J. P. B., Jacob, I., Souza, L. R., Rodrigues, A. V., . . . & Rodrigues, R. R. (2022). Biodiversity responses to restoration across the Brazilian Atlantic Forest. *Science of The Total Environment* , 153403.*https://doi.org/10.1016/j.scitotenv.2022.153403*

Rozendaal, D. M., Bongers, F., Aide, T. M., Alvarez-Dávila, E., Ascarrunz, N., Balvanera, P., . . . & Poorter, L. (2019). Biodiversity recovery of Neotropical secondary forests. *Science advances* , *5* (3), eaau3114*https://www.science.org/doi/10.1126/sciadv.aau3114*

Santo-Silva, E. E., Almeida, W. R., Tabarelli, M., & Peres, C. A., 2016. Habitat fragmentation and the future structure of tree assemblages in a fragmented Atlantic Forest landscape*. Plant Ecology* , 217, 1129–1140.*https://doi.org/10.1007/s11258-016-0638-1*

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araújo-Filho, J. C., Oliveira, J. B., & Cunha, T. J. F. (2018). *Sistema brasileiro de classificação de solos* . Brasília (DF): Embrapa.

Sarmento, P.S.M., Ferreira, L.V., & Gastauer, M. (2021). Natural regeneration triggers compositional and functional shifts in soil seed banks. *Science of the Total Environment* , 753, 141934.*https://doi.org/10.1016/j.scitotenv.2020.141934*

Silva, K. D. A., Martins, S. V., Miranda, A., & Campos, W. H. (2015). Semeadura direta com transposição de serapilheira como metodologia de restauração ecológica. *Revista Árvore* , 39(5), 811-820. *https://doi.org/10.1590/0100-67622015000500004*

Silva, K. D. A., Martins, S. V., Miranda-Neto A., Demolinari, R. D. A., & Lopes, A. T. (2016). Restauração florestal de uma mina de bauxita: avaliação do desenvolvimento das espécies arbóreas plantadas.*Floresta e Ambiente* , 23(3), 309-319.*https://doi.org/10.1590/2179-8087.142515*

Silva, K. D. A., Martins, S. V., Miranda A., & Lopes, A. T. (2018). Litter stock in a forest in process of restoration after bauxite mining. Rodriguésia, v. 69, p. 853-861, 2018. <https://doi.org/10.1590/2175-7860201869240>

Silva, K. D. A., Martins, S. V., Miranda A., & Lopes, A. T. (2019). Soil seed banks in a forest under restoration and in a reference ecosystem in Southeastern Brazil. *Floresta e Ambiente* , 26(4): e20190047.*https://doi.org/10.1590/2179-8087.004719*

Silva, K. D. A., Martins, S. V., & Miranda-Neto A. (2020). 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. 1-11, 2020. <https://doi.org/10.30564/re.v2i4.2609>.

Silva, C. V., Martins, S. V., Villa, P. M., Kruschewsky, G. C, Dias, A. A., & Nabeta, F. H. (2021a). Banco de semillas de relaves mineros como indicador de recuperación de vegetación en Mariana, Brasil. *Revista de Biología Tropical* , *69* (2), 700-716. *https://doi.org/10.15517/rbt.v69i2.41800*

Silva, A. C. A., Martins, S. V., & Balestrin, D. (2021b). Soil Seed Bank as a Bioindicator to Identify Invasive Species. *Floresta (Online)* , 51(3), 760-766.*http://dx.doi.org/10.5380/rf.v51i3.72709*

Shepherd GJ. (2010). Fitopac 2.1. Campinas, Brasil: Departamento de Botânica, Universidade Estadual de Campinas.

Shi, Y. F., Wang, Z. R., Xu, B. X., Huo, J. Q., Hu, R., Zhao, Y., & Zhang, Z. S. (2022). Rainfall amount determines annual herb controls over soil seed bank and its similarity with vegetation in the Tengger Desert. *Ecological Processes* , *11* (1), 1-11.*https://doi.org/10.1186/s13717-021-00346-w*

Spletozer, A. G., da Silveira, L. J., Sato, A. Y., Lorenzon, A. S., Zanuncio, J. C., & Dias, H. C. T. (2021). Surface runoff from an area undergoing soil rehabilitation after bauxite mining in southeastern Brazil. *Land Degradation & Development* , *32* (9), 2715-2725.*https://doi.org/10.1002/ldr.3948*

Tonetti, V., Niebuhr, B. B., Ribeiro, M., & Pizo, M. A. (2022). Forest regeneration may reduce the negative impacts of climate change on the biodiversity of a tropical hotspot. *Diversity and Distributions* . 00, 1-16.*https://doi.org/10.1111/ddi.13523*

United Nations. (2022). Decade on Ecosystem Restoration (2021-2030). Disponível em <https://www.decadeonrestoration.org/> [accessed on September 02, 2022]

USGS. (2022). Mineral commodity summaries 2022 - Bauxite and Alumina. United States: US Geological Survey.

Viani, R. A. G., Vidas, N. B., Pardi, M. M., Castro, D. C. V., Gusson, E., & Brancalion, P.H. (2015). Animal-dispersed pioneer trees enhance the early regeneration in Atlantic Forest restoration plantations. *Natureza & Conservação* , 13(1), 41-46.*https://doi.org/10.1016/j.ncon.2015.03.005*

Villa, P. M., Martins, S. V., Rodrigues, A. C., Vieira, N., Bonilla, M. A., & Ali, A. (2019). Testing species abundance distribution models in tropical forest successions: implications for fine-scale passive restoration. *Ecological Engineering* , 135, 687-694.*https://doi.org/10.1016/j.ecoleng.2019.05.015*

Villa, P. M., Ali, A., Martins, S. V., Oliveira Neto, S. N., Rodrigues A. C, Teshome, M, ... & Gastauer, M. (2020). Stand structural attributes and functional trait composition overrule the effects of functional divergence on aboveground biomass during Amazon forest succession. *Forest Ecology and Management* , *477* , 118481.*https://doi.org/10.1016/j.foreco.2020.118481*

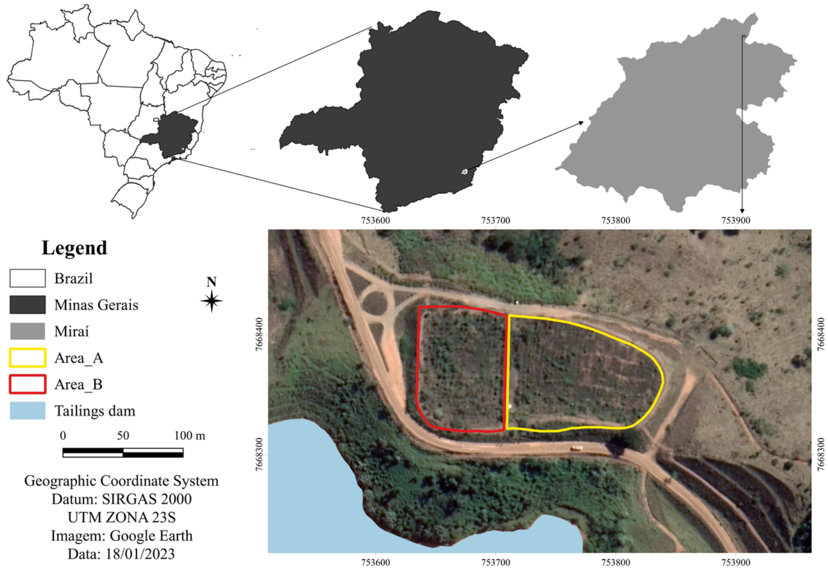
Villa, P. M., Martins, S. V., Diniz, É. S., Oliveira Neto. S. N., Neri, A. V., Pinto-Junior, H., ... & Ali, A. (2021). Taxonomic and functional beta diversity of woody communities along Amazon Forest succession: The relative importance of stand age, soil properties and spatial factor. *Forest Ecology and Management* , *482* , 118885.*https://doi.org/10.1016/j.foreco.2020.118885*

Vilas Boas, H. F., Almeida, L. F., Teixeira, R. S., Souza, I. F., & Silva, I. R. (2018). Soil organic carbon recovery and coffee bean yield following bauxite mining.*Land Degradation & Development* , *29* (6), 1565-1573.*https://doi.org/10.1002/ldr.2949*

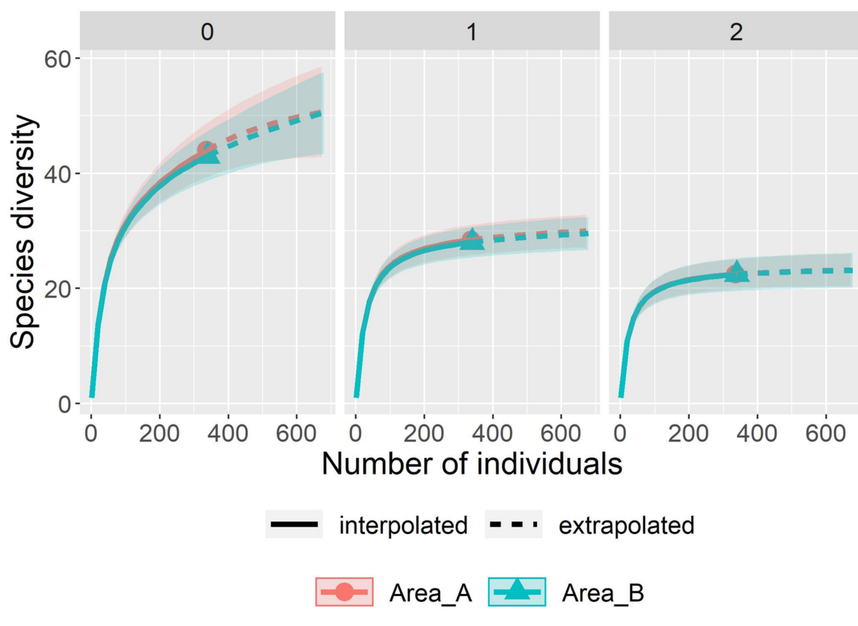
Volpato, G. H, Martins, S. V, & Cosimo, L. H. E. (2018). Avifauna em florestas em processo de restauração pós-mineração de bauxita em Minas Gerais. MG. BIOTA, 10, 18-45.

**Hosted file**

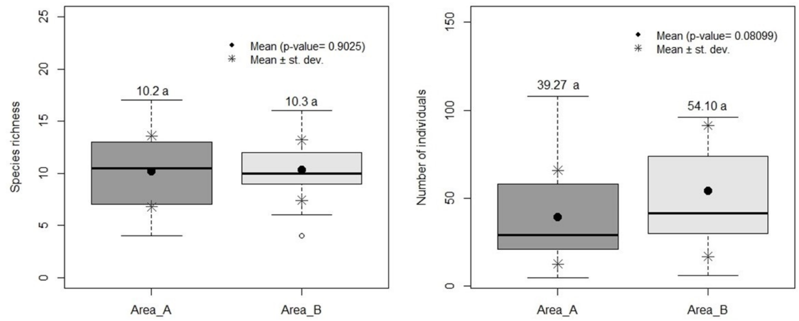
`Page Title.docx` available at https://authorea.com/users/580106/articles/621320-relationship-between-soil-seed-bank-and-forest-restoration-techniques-on-areas-around-bauxite-mining-environment

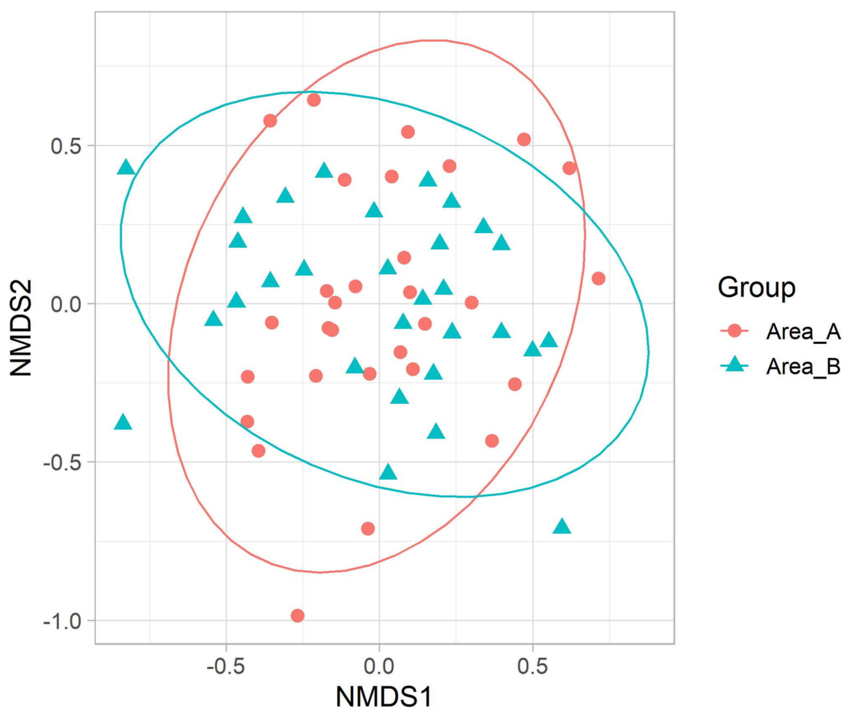


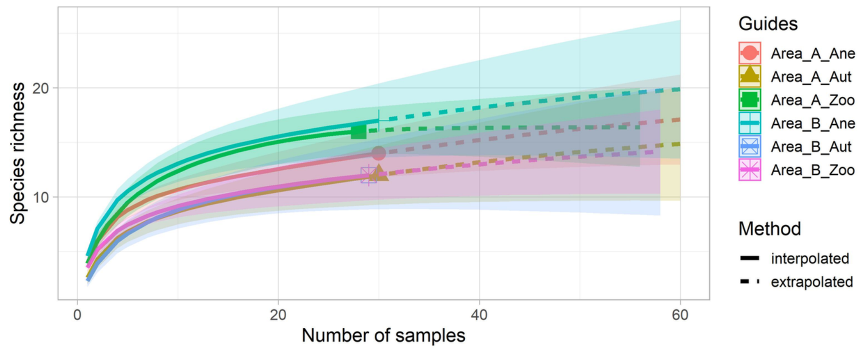
Legend
Brazil
Minas Gerais
Miraí
Area_A
Area_B
Tailings dam
0
50
100 m
N
Geographic Coordinate System
Datum: SIRGAS 2000
UTM ZONA 23S
Imagem: Google Earth
Data: 18/01/2023
753600
753700
753800
753900
7668400
7668300

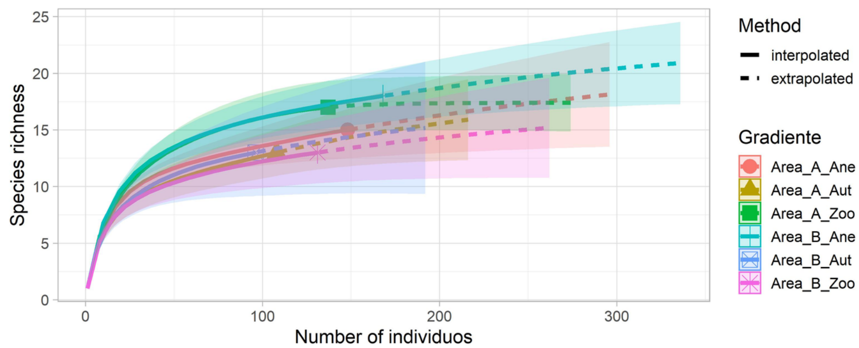



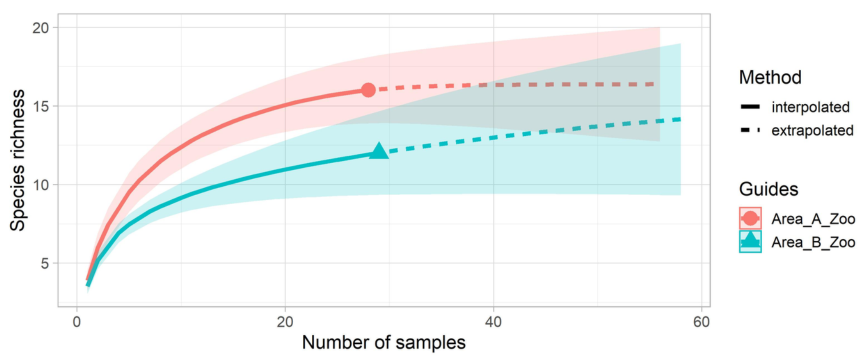
0
1
2
Species diversity
60
40
20
0
200
400
600
Number of individuals
interpolated
extrapolated
Area_A
Area_B

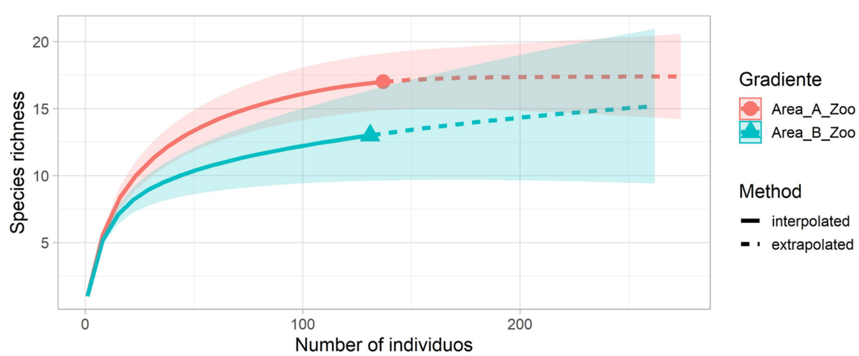

Species richness
Mean (p-value= 0.9025)
Mean ± st. dev.
10.2 a
10.3 a
Area_A
Area_B
Number of individuals
Mean (p-value= 0.08099)
Mean ± st. dev.
39.27 a
54.10 a
Area_A
Area_B

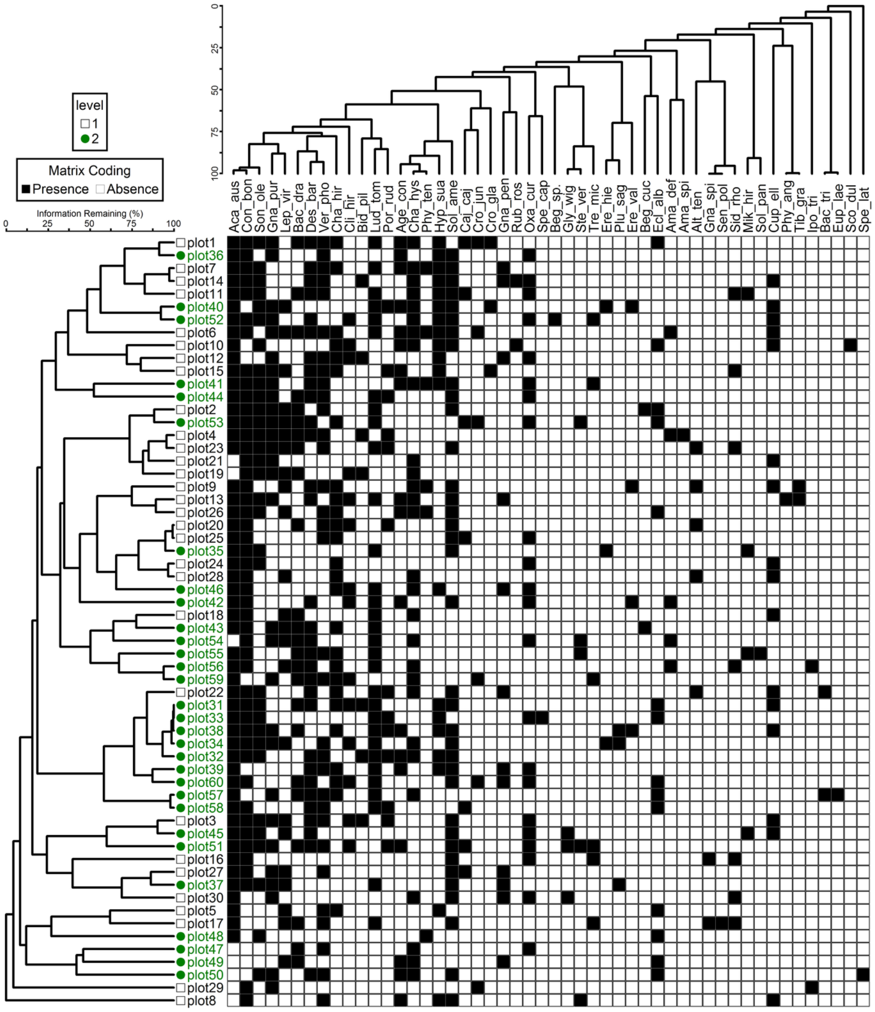

NMDS2
NMDS1
Group
Area_A
Area_B


Species richness
Number of samples
Guides
Area_A_Ane
Area_A_Aut
Area_A_Zoo
Area_B_Ane
Area_B_Aut
Area_B_Zoo
Method
interpolated
extrapolated


Species richness
Number of individuos
Method
interpolated
extrapolated
Gradiente
Area_A_Ane
Area_A_Aut
Area_A_Zoo
Area_B_Ane
Area_B_Aut
Area_B_Zoo


Species richness
Number of samples
Method
interpolated
extrapolated
Guides
Area_A_Zoo
Area_B_Zoo


Species richness
Number of individuos
Gradiente
Area_A_Zoo
Area_B_Zoo
Method
interpolated
extrapolated


level
1
2
Matrix Coding
Presence
Absence
Information Remaining (%)
0
25
50
75
100
Aca_aus
Con_bon
Son_ole
Gna_pur
Lep_vir
Bac_dra
Des_bar
Ver_pho
Cha_hir
Cli_hir
Bid_pil
Lud_tom
Por_rud
Age_con
Cha_hys
Phy_ten
Hyp_sua
Sol_ame
Caj_caj
Cro_jun
Cro_gla
Gna_pen
Rub_ros
Oxa_cur
Spe_cap
Beg_sp.
Gly_wig
Ste_ver
Tre_mic
Ere_hie
Plu_sag
Ere_val
Beg_cuc
Ecl_alb
Ama_def
Ama_spi
Alt_ten
Gna_spi
Sen_pol
Sid_rho
Mik_hir
Sol_pan
Cup_ell
Phy_ang
Tib_gra
Ipo_tri
Bac_tri
Eup_lae
Sco_dul
Spe_lat
plot1
plot36
plot7
plot14
plot11
plot40
plot52
plot6
plot10
plot12
plot15
plot41
plot44
plot2
plot53
plot4
plot23
plot21
plot19
plot9
plot13
plot26
plot20
plot25
plot35
plot24
plot28
plot46
plot42
plot18
plot43
plot54
plot55
plot56
plot59
plot22
plot31
plot33
plot38
plot34
plot32
plot39
plot60
plot57
plot58
plot3
plot45
plot51
plot16
plot27
plot37
plot30
plot5
plot17
plot48
plot47
plot49
plot50
plot29
plot8