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Natural regeneration for restoration of degraded areas after bauxite mining: A case study in the Eastern Amazon

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A R T I C L E I N F O

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A B S T R A C T

Natural regeneration is becoming more frequently used on a global level as a method of ecological restoration after mining operations. The objective of this study was to investigate forest restoration as a function of the exclusive use of natural regeneration in systems with two (NR2) and seven (NR7) years of age after bauxite mining in Eastern Amazon, Brazil (3° 14′ 51″–3° 15′ 48″ S and 47° 44′ 14″–47° 43′ 09″ W). Soil's physical and chemical parameters (organic matter, bulk density, porosity, infiltration, and fertility), landscape-level quantification of vegetation in the areas surrounding the study sites and attributes of the established vegetation (abundance of individuals and families, Shannon diversity index, evenness index, and ecological dominance index) were assessed. The method of natural regeneration, in seven years, was efficient to occupy and cover the soil by regenerating tree and shrub species, as well to contribute to the recovery of important surface-depth attributes of the quality of rebuilt soils, such as organic matter, nutrient availability, density, porosity, and water infiltration. The regenerating tree and shrub species had low diversity and high dominance of a few pioneer species, which indicates the necessity of introducing early and late secondary successional species to correct the successional trajectory in order to ensure the ecosystem restoration.

1. Introduction

The use of natural regeneration for restoration of mined areas has been widely used by mining companies in different regions around the world (Martins et al., 2020), including the Brazilian Amazon (Parrotta et al., 1997; Salomão et al., 2007; Salomão, 2015). Natural regeneration techniques are especially relevant in eastern Amazon due to the extensive areas of bauxite mining in this region and have been used in restoration experiments after mining operations (Ribeiro et al., 2019).

The use of the initial regeneration is essential to attain an efficient trajectory under low costs (Chazdon and Guariguata, 2016; Latawiec et al., 2016). However, the success of natural regeneration depends on factors such as substrate quality, environmental conditions, presence of propagules and distribution and conservation of remnant forests (Pickett et al., 2001; Vale et al., 2015; César et al., 2016; Ribeiro et al., 2021).

Among the models and theories related to the trajectory of restoration processes in an ecosystem (Cadenasso et al., 2003; Pulsford et al., 2016), Pickett et al. (2008) states that there are three processes that determine the restoration success: (1) differential availability of favorable sites and conditions for vegetation development; (2) continuous availability of vegetation that can be added to the system, and (3) presence of species that have different growth habits and ecological requirements.

The first step in the restoration process after terrain reshaping is the structuring phase wherein a canopy dominated by pioneer species is formed (Rodrigues et al., 2009). In this phase, which varies according to the degree of degradation and the composition and diversity of established tree species (Salomão et al., 2012), it is expected that there will be enough shade to eliminate pioneer species such as exotic grasses (Engel and Parrota, 2001), and start a forest ecosystem (Bizuti et al., 2016). In addition, the ecosystem has a gradual increase in food sources favoring movement different populations of fauna to induce the introduction of propagules (Crouzeilles and Curran, 2016). This phase should promote the recuperation of soil attributes, especially the accumulation of

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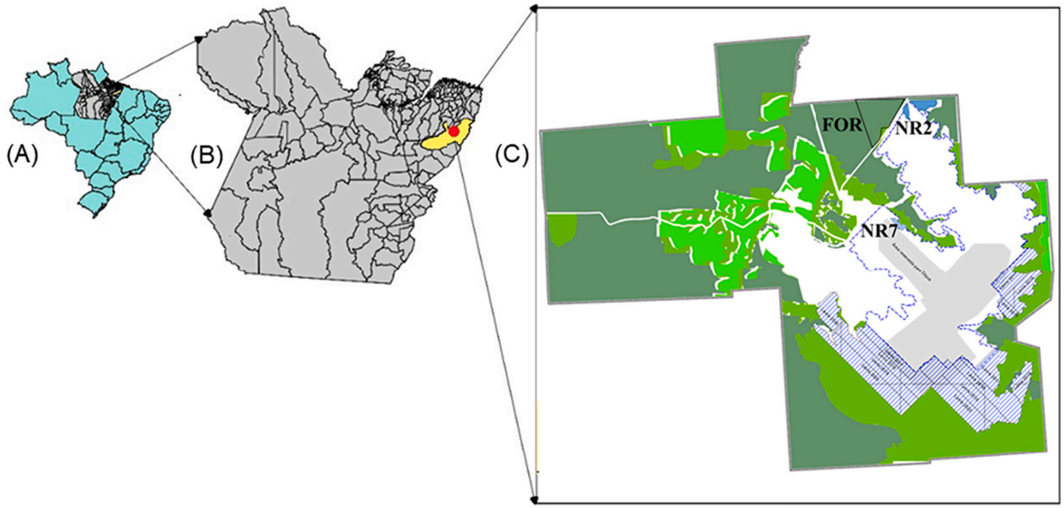


Fig. 1. Study area location in Brazil (a), and the state of Pará (b), municipality of Paragominas (in yellow with red point), where the Platô Miltônia 3 mining site and the experimental areas appear amplified (c). NR2 and NR7: Forest restoration with natural regeneration at two and seven years. FOR: reference native forest. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

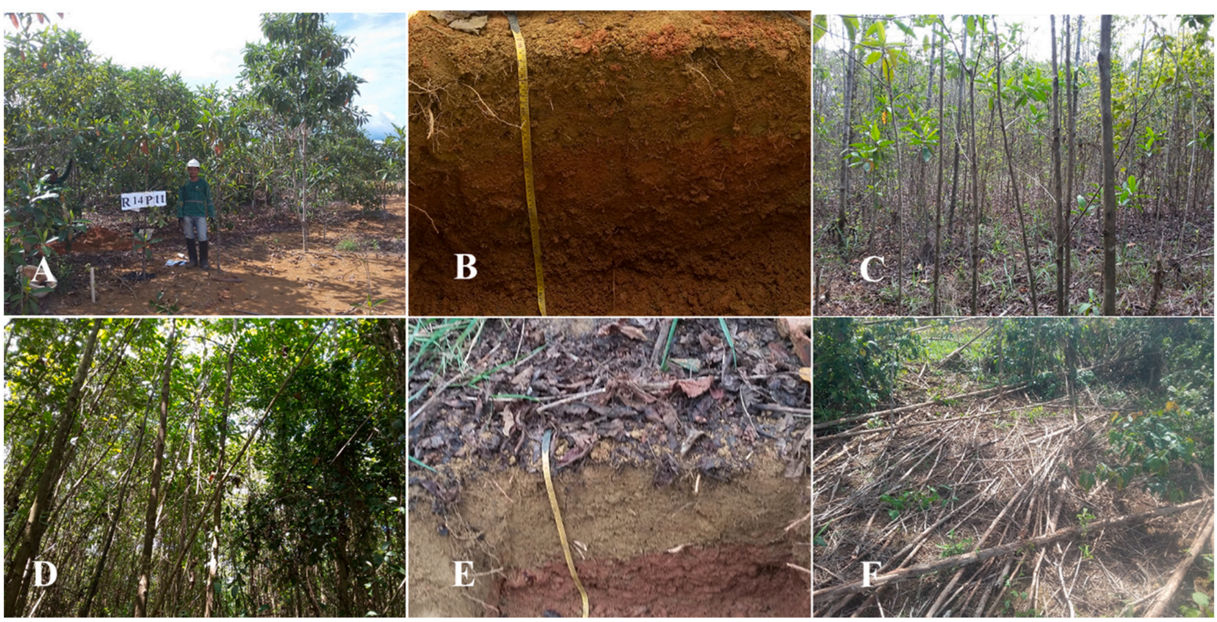


Fig. 2. Two-year-old restoring ecosystem with Natural Regeneration: regenerating pioneer species (A); profile of reconstructed soil (B) and understory with pioneer tree species (C). Seven-year-old restoring ecosystem with Natural Regeneration: regenerating pioneer species (D); profile of reconstructed soil (E) and understory with dead individuals of pioneer tree species (F).

organic matter (Barros et al., 2013) and improvement of structural conditions that favor ecological dynamics and processes that are controlled by the soil (Walker and Reddell, 2007). Due to factors such as senescence, competitive exclusion, and adverse environmental conditions, many pioneer species tend to die out and be replaced by initial secondary species, which signals a transition phase in the trajectory of the ecosystem. According to Walker and Del Moral (2008), and Brancalion et al. (2015), the consequences of these processes can favor the creation of a new canopy dominated by initial secondary species. These species would consolidate the forest succession or lead to an abrupt loss of canopy and a regression to the initial stage of recuperation. In this case, open areas would have low diversity and density of vegetation, and/or inadequate conditions for the development of initial secondary species.

When there is a regression in the successional trajectory of an ecosystem, a large part of the benefits accumulated through the implantation of the community of pioneer species can be lost, thus causing a return to conditions of the initial structuring phase (Walker and Del Moral, 2008). Knowledge of the interaction of the regenerating species during each phase of a specie's life cycle is fundamental to understand transitional processes and therefore how to proceed with restoration.

The hypothesis used in this study is that the exclusive use of natural regeneration for restoration of a bauxite mine in the eastern Amazon is insufficient to promote, in the short term, improvements in the physical and chemical soil attributes and forest succession, with regenerating native species with high diversity and low ecological dominance. In this context, the objective of this study was to investigate the efficiency of natural regeneration in the improvement of soil attributes as well as the success of forest restoration in sites under restoration during a short time (2 and 7 years) after bauxite mining.

Table 1
Strata, criteria, and area of plots used for sampling plant species in the different restoration treatments in areas degraded by bauxite mining in the eastern Amazon, Brazil.

Strata	Criteria	Plot area
Superior	DBH $\geq$ 5 cm	200 m^2 (10 × 20 m)
Intermediate	DBH $\geq$ 1 cm and < 5 cm	100 m^2 (10 × 10 m)
Inferior	$\geq$ 30 cm height and < 1 cm DBH	10 m^2 (1 × 10 m)

*DBH: diameter at breast height at 1.30 m above the soil.

2. Material and methods

2.1. Study area

This study was carried out in the bauxite mining area Platô Miltônia 3, which belongs to the mining company Mineração Paragominas S.A., part of the Hydro group, in the municipality of Paragominas, Pará state, Brazil (Fig. 1). The climate is Aw in the Köppen classification system, with a dry period between June and December (Bastos et al., 2005), annual average temperature of 25 °C, annual rainfall between 2250 and 2500 mm, and air humidity of 85% (SEPOF, 2014).

Bauxite mining in the region is conducted using strip mining, which consists of several stages including vegetation suppression, soil removal, and topsoil saving for later use in soil reconstruction, regolith excavation up the bauxite layer (about 10 m), and extraction and transport of the mineral. The material with no economic value, defined as sterile material is used to fill the open pits during the terrain reshaping to the topographic conditions of the local landscape. The topsoil is then spread over the sterile material to finalize the initial step of soil reconstruction and forest restoration. The methods of forest restoration include natural regeneration, seedling planting, and nucleation.

This study was developed in two areas submitted to ecological restoration using natural regeneration with ages since establishment of a) two years (NR2), implemented in March 2014, and b) seven years (NR7), implemented in May 2009 (Fig. 2). The procedures carried out in these areas after bauxite mining consisted of a) terrain reshaping by spreading of sterile substrate, b) covering the sterile substrate with topsoil (0.2 to 0.3 m) from the same area that was removed before the bauxite mining, in order to promote regeneration of propagules that are present in this material, and c) isolation of the area with no further anthropogenic intervention following completion of steps "a" and "b". To evaluate the ecological restoration of these sites, a fragment of native ombrophilous dense forest (FOR), was used as a reference ecosystem. This forest was submitted to logging up 2003.

The soil of FOR is classified as a typical Dystrophic Yellow Latosol, according to the Brazilian Soil Classification System (Santos et al., 2018), with a very clayey texture (clay content >700 g kg^{-1}), corresponding to Typic Hapludox in the USA Soil Taxonomy (Soil Survey Staff, 2014). The soil texture at the NR2 and NR7 sites contains more than 700 g kg^{-1} of clay and has flat to gently undulating relief. NR2 is adjacent to FOR, while NR7 is adjacent to a fragment of 50-year-old secondary native forest 100 m distant from a native forest fragment (Fig. 1).

2.2. Experimental design for soil and vegetation sampling

At each site 15, 200 m^2 (20 m × 10 m) plots were randomly established. In January 2016 disturbed and undisturbed soil samples were collected, soil water infiltration testing was done in the field, and a tree and shrub vegetation survey was conducted.

Soil samples were taken at depths 0–0.1; 0.1–0.2, and 0.2–0.4 m and were randomly collected within each plot. The disturbed soil samples were collected at three points in each plot, homogenized, and one composite sample was then taken for each depth and plot. Undisturbed soil samples were taken by extracting a 1000 cm^3 (10 × 10 × 10 cm) monolith. The monolith was treated with a mixture of glue, water, and hydrated alcohol in a proportion of 5:4:1, respectively. The variables analyzed using these undisturbed soil samples were density and total porosity, with 15 repetitions per treatment and depth. Soil water infiltration testing was done next to where the disturbed and undisturbed soil samples were taken in each plot, with 15 repetitions per treatment.

To characterize the natural regeneration systems, a survey of the presence of pebble- and gravel-sized ferruginous concretions was conducted, following the method of Santos et al. (2015), using five 1 × 1 × 0.5 m trenches that were randomly located within each study area. Concretions were observed in these areas between 0.3 and 0.5 m in the soil, NR2 and NR7 having concretions in about 10 ± 5% and 50 ± 10% in the sampled depth, respectively.

Vegetation sampling had three subplots, where the inferior, intermediate, and superior strata were sampled (Table 1). Data collection consisted of measuring height and DBH (diameter at breast height) at 1.30 m above the soil, and collect botanical material for scientific identification of shrub and tree species in the field and at the laboratory of EMBRAPA Eastern Amazon (IAN).

2.3. Variables analyzed

a) Physical and chemical soil attributes

The chemical soil attributes analyzed were pH in H_2O; potential acidity (H + Al) ($cmol_c$ dm^{-3}); exchangeable calcium (Ca), magnesium (Mg), and aluminum (Al) ($cmol_c$ dm^{-3}), available phosphorus (P) (mg dm^{-3}), potassium (K) ($cmol_c$ dm^{-3}), and organic matter (O.M.) (g kg^{-1}). The methods and laboratory procedures are described in Teixeira et al. (2017).

With respect to physical soil attributes, soil density was measured using the paraffin clod method as described by Viana (2008). Total porosity (Pt) was calculated using the equation Pt = (1 - Ds/Dp), with Dp = 2.65 kg dm^{-3}, a commonly used value for mineral soils. Soil water infiltration was determined using the concentric ring method, which consists of a large metal ring (20 cm diameter and 20 cm height) and a smaller ring (10 cm diameter and 20 cm height). The small ring was placed inside the larger one, and both rings were fixed into the soil surface. Accumulated infiltration (IA) was calculated, which is the sheet of water that infiltrated the soil as a function of accumulated time (T). Using *IA* the parameters *k* and *a* were obtained and used in a non-liner regression model proposed by Kostiakov (1932):

$$IA = kT^a$$

By deriving the function of the estimate of infiltration as a function of time, the model for the potential velocity of soil water infiltration is obtained (VI):

$$VI = \frac{dIA}{dT} = kaT^{a-1}$$

For quantification of the population of plant species in the areas surrounding the study sites, images were used from the Landsat 8 satellite, Operational Land Imager (OLI) sensor, orbit/point 223/62, from September 21, 2016, obtained from the site Earth Explorer. The images had resolution of 30 m with RGB color composition on bands 6-5-4. A 10 km radius was demarcated, starting from the center of the mined area to be restored, according to the recommendations of Crouzeilles and Curran (2016), for evaluation of areas for restoration at a landscape scale.

Subsequently, Image pre-processing procedures were done, which consisted of cropping, radiometric correction, and georeferencing. The image processing steps were done through supervised classification by the maximum likelihood algorithm wherein the following landscape classes are defined: (1) Dense Forest: ombrophilous lowland dense forest and forest under advanced succession; (2) Forest in an intermediate stage of succession; (3) Forest in an initial stage of succession,

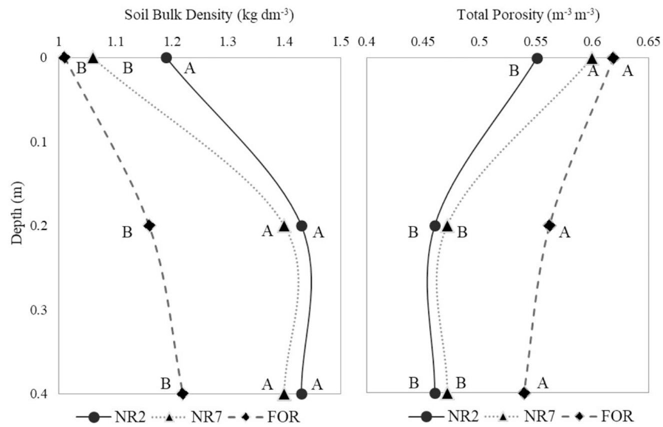


Fig. 3. Soil bulk density (Ds) and total porosity (Pt) in systems under natural regeneration for two years (NR2), seven years (NR7), and a reference native forest (FOR) in depths 0–0.1, 0.1–0.2, and 0.2–0.4 m, in a bauxite mining area in the eastern Amazon, Brazil.

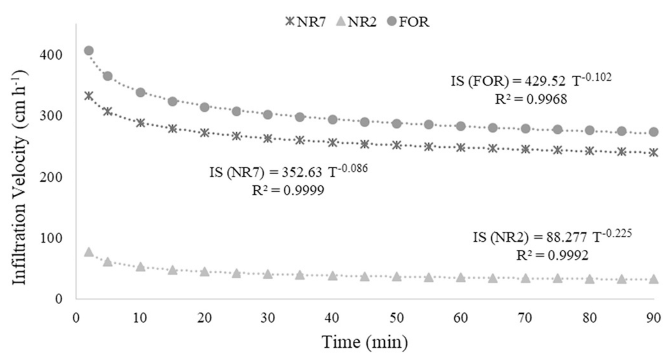


Fig. 4. Infiltration velocity (cm h^{-1}) of soil water in a restoration area after bauxite mining under natural regeneration for two years (NR2), seven years (NR7), and a reference native forest (FOR), eastern Amazon, Brazil.

dominated by areas with degraded pastures and abandoned agricultural fields; (4) Exposed soil in areas in a site preparation phase for implantation of agricultural or cattle ranching activities, and areas recently mined or not assigned for restoration; (5) Burned areas or deforestation; (6) Underbrush or low-laying vegetation in agricultural fields, productive pastures, grasses; (7) Water.

After treatment and classification of the images, the post-classification step was done, which consisted of computing the area occupied by each landscape class. The pre-treatment and treatment of orbital images was done using the software Qgis 3.0.

b) Regenerating vegetation

The variables calculated for the three sampled strata were species richness, number of families, abundance of individuals, the Shannon (H′) diversity index, the Pielou evenness index (j), and the ecological dominance index (D = 1-Simpson index), as described by Hammer (2020). Calculations were performed through the Software PAST 4.02.

The ecological dominance index varies from zero (all species are equally present) to one (one species completely dominates the community). Using as a base the studies by Amaral et al. (2009) and Miranda Neto et al. (2012), the ecological group of each species was determined, which were divided into a) pioneer, b) initial secondary, c) late secondary, and d) climax.

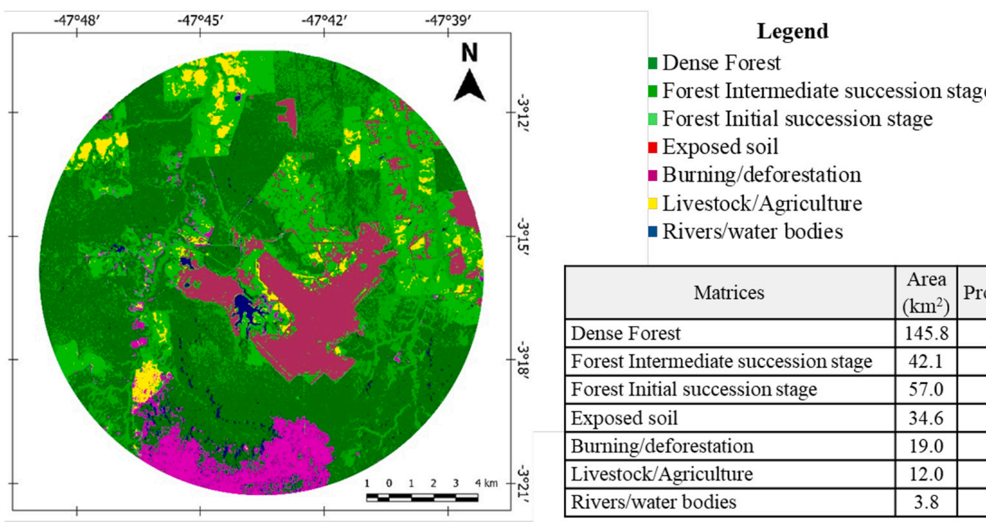
Table 4
The most abundant tree and shrub species in each vegetation strata with the percent occupation and the ecological group (GE - P: Pioneer; SI: Initial Secondary; ST: Late Secondary) in the natural regeneration of a restoration area after bauxite mining of two (NR2) and seven years (NR7), and in a reference native forest fragment (FOR), eastern Amazon, Brazil.

Position	System/strata	Percentage	GE
	NR2 superior		
1°	*Croton matourensis* Aubl.	85.2	P
2°	*Solanum* sp.	11.1	P
3°	*Byrsonima crassifolia* (L.) Kunth	3.7	SI
		Total: 100%	
	NR2 intermediate		
1°	*Croton matourensis* Aubl.	48.5	P
2°	*Trema micrantha* (L.) Blume	16.6	P
3°	*Cecropia* sp.	10.2	P
4°	*Zanthoxylum pentandrum* (Aubl.) R.A. Howard	7.2	P
5°	*Solanum* sp.	5.1	P
		Total: 87.6%	
	NR2 inferior		
1°	*Cecropia* sp.	33.3	P
2°	*Croton matourensis* Aubl.	11.9	P
3°	*Solanum* sp.	11.9	P
4°	*Vismia guianensis* (Aubl.) Choisy	9.5	P
5°	*Solanum fulvidum* Bitter	9.5	P
		Total: 76.1%	
	NR7 superior		
1°	*Croton matourensis* Aubl.	52.6	P
2°	*Byrsonima crassifolia* (L.) Kunth	14.9	SI
3°	*Cecropia* sp.	13.7	P
4°	*Casearia javitensis* Kunth	8.8	SI
5°	*Vismia guianensis* (Aubl.) Choisy	6.4	P
		Total: 96.4%	
	NR7 intermediate		
1°	*Croton matourensis* Aubl.	49.5	P
2°	*Casearia javitensis* Kunth	12.5	SI
3°	*Vismia guianensis* (Aubl.) Choisy	12.1	P
4°	*Guatteria punctata* (Aubl.) R.A.Howard	10.3	P
5°	*Byrsonima crassifolia* (L.) Kunth	5.0	P
		Total: 89.4%	
	NR7 inferior		
1°	*Vismia guianensis* (Aubl.) Choisy	37.5	P
2°	*Guatteria punctata* (Aubl.) R.A.Howard	31.3	P
3°	*Croton matourensis* Aubl.	12.5	P
4°	*Cecropia distachya* Huber	12.5	P
5°	*Cecropia* sp.	6.2	P
		Total: 100%	
	FLO superior		
1°	*Apeiba albiflora* Ducke	14.6	SI
2°	*Guatteria punctata* (Aubl.) R.A.Howard	9.7	P
3°	*Talisia microphylla* Uittien.	8.4	P
4°	*Inga thibaudina* DC.	6.2	P
5°	*Eschweilera coriacea* (DC.) S.A.Mori	5.0	ST
		Total: 43.9%	
	FLO intermediate		
1°	*Rinorea flavescens* (Aubl.) Kuntze	19.0	SI
2°	*Talisia microphylla* Uittien.	11.5	P
3°	*Chrysophyllum prieurii* A.DC.	9.8	ST
4°	*Eschweilera coriacea* (DC.) S.A. Mori	9.4	ST
5°	*Amphiodon effusus* Huber	6.9	SI
		Total: 56.6%	
	FLO inferior		
1°	*Rinorea flavescens* (Aubl.) Kuntze	29.3	SI
2°	*Eschweilera coriacea* (DC.) S.A.Mori	9.8	ST
3°	*Talisia microphylla* Uittien.	7.3	P
4°	*Chrysophyllum prieurii* A.DC.	6.1	ST
5°	*Duguetia flagellaris* Huber	6.1	ST
		Total: 58.6%	

Table 2
Substrate chemical attributes in the natural regeneration of a restoration area after bauxite mining of two (NR2) and seven years (NR7), and in a reference native forest (FOR) in depths 0–0.1, 0.1–0.2, and 0.2–0.4 m, eastern Amazon, Brazil.

	O.M.	pH_{H2O}	P	K	Ca	Mg	Al	SB	CEC
	g kg^{-1}		(mg dm^{-3})	cmol$_c$ dm^{-3}					
	0–0.1 m								
NR2	17.4c	5.00a	1.75^a	0.06b	0.64b	0.26b	0.43b	0.98b	6.77c
NR7	26.2b	5.08a	1.97^a	0.15a	1.09a	0.49a	0.34b	1.73a	9.58b
FOR	32.8a	4.39b	2.00a	0.09b	0.46b	0.13c	2.10a	0.70c	14.0a
	0.1–0.2 m								
NR2	14.2b	4.56b	0.82b	0.03b	0.27b	0.11b	0.80b	0.41b	5.03c
NR7	21.6a	4.92a	1.20^a	0.08a	0.74a	0.27a	0.45c	1.11a	8.16b
FOR	26.0a	4.24c	1.19^a	0.08a	0.13b	0.07b	2.14a	0.29b	11.3a
	0.2–0.4 m								
NR2	3.97b	4.52b	0.55b	0.03b	0.20b	0.10b	0.13b	0.33b	3.03c
NR7	13.0a	5.03a	1.02^a	0.07a	0.51a	0.20a	0.31b	0.79a	5.16b
FLO	14.37a	4.32b	0.74b	0.07a	0.16b	0.05c	1.52a	0.29b	6.65a

Means followed by the same letter are not different at 5% probability by Tukey's test; ns = not significant; $n = 15$.



Matrices	Area (km^2)	Proportion
Dense Forest	145.8	0.46
Forest Intermediate succession stage	42.1	0.13
Forest Initial succession stage	57.0	0.18
Exposed soil	34.6	0.11
Burning/deforestation	19.0	0.06
Livestock/Agriculture	12.0	0.04
Rivers/water bodies	3.8	0.01

Fig. 5. Thematic map of soil use classes at a landscape scale, and the proportion of the studied areas occupied by these classes in 2016, considering an area defined by a radius of 10 km from the center of the mined area.

2.4. Statistical analysis

Descriptive statistics was used for the vegetation data. The data of soil physical and chemical attributes were tested for normality using the Shapiro-Wilk test, and non-normal data were transformed using the Box-Cox transformation. Subsequently, Analysis of Variance (ANOVA) was done, followed by the Tukey test for mean comparison at a 5% probability level. Soil and vegetation data were also analyzed using Principal Components Analysis (PCA).

3. Results and discussion

3.1. Soil physical and chemical attributes

There were no significant differences between NR7 and FOR at 0–0.1 m in the profile for soil bulk density (Ds) and total porosity (Pt) (Fig. 3). These results are highly significant for ecological restoration because they demonstrate that in seven years natural regeneration was able to stimulate the recovery of important soil physical attributes in the surface depth. It is important to emphasize that there was no soil movement involved in management activities to reduce compaction in the study areas. Therefore, the decrease in Ds and the increase in Pt in the surface soil at NR7 could be related to the evolution of soil structure that occurred in this area over 7 years, which was stimulated by the effect of litterfall from the regenerating species that were thriving in this site. It has been established that litterfall exerts strong effects on the surface soil depth (Frouz et al., 2009; Pries et al., 2017; Brasil Neto et al., 2021). On the other hand, the greatest value for density, accompanied by the lowest value for total porosity was in the more recently established area (NR2), which could be a reflection of the loss of soil structure due to the removal of the soil and the subsequent terrain reshaping, which results in physical limitations due to substrate compaction.

In the two lower soil depths (0.1–0.2 and 0.2–0.4 m) there was an increase in density and a decrease in total porosity compared to 0–0.1 m in the systems NR2 and NR7. This is associated with the presence of a compacted layer (sterile layer), where there is usually an increase in pebble- and gravel-sized ferruginous concretions, besides a more compacted layer due to the process of site preparation using heavy machinery. This compaction in the lower soil depths represents a strong limitation to the vegetation regeneration process, since compaction in these depths impedes root development (Acton et al., 2011) with increase in plant mortality (Salomão et al., 2007).

The curves for soil water infiltration were similar in NR7 and FOR, with values larger than those for NR2 (Fig. 4). The improvement in the quality of soil physical attributes in the surface depth at NR7 is confirmed by greater water infiltration, which was four times greater at

Table 3
Variables of vegetation diversity for the strata superior (DBH ≥ 5 cm), intermediate (DBH ≥ 1 cm and < 5 cm), and inferior (≥30 cm height < 1 cm DBH) in a restoration area after bauxite mining using natural regeneration (NR2 and NR7), and a reference native forest (FOR), eastern Amazon, Brazil.

Parameters	Treatments		
	NR2	NR7	FOR
Superior strata			
Species richness	3	10	69
Number of families	3	9	38
Abundance (ind ha^{-1})	90 ± 187	1096 ± 813	1346.6 ± 157
Shannon diversity index (H')	0.03	0.67	2.43
Pielou evenness(j)	0.04	0.56	0.91
Ecological dominance (D)	0.38	0.65	0.12
Intermediate strata			
Species richness	12	14	66
Number of families	9	12	36
Abundance (ind ha^{-1})	1566.7 ± 1488	1873.3 ± 1401	3480 ± 1377
Shannon diversity index (H')	0.75	1.05	2.27 a
Pielou evenness(j)	0.51	0.76	0.87 a
Ecological dominance (D)	0.62	0.44	0.15 b
Inferior strata			
Species richness	11	5	23
Number of families	9	4	15
Abundance (ind ha^{-1})	2800.0 ± 4565	1066.7 ± 1387	5466.7 ± 2569
Shannon diversity index (H')	0.52	0.12	0.96
Pielou evenness(j)	0.44	0.18	0.74
Ecological dominance (D)	0.50	0.52	0.48

*Means followed by different letters in rows indicate statistical difference by the Tukey test (5% probability).

NR7 than the rates observed in Eucalyptus plantations and abandoned pasture on heavy clay Oxisols in the same region as the current study (Rocha et al., 2016).

Soil water infiltration is principally influenced by soil structure, especially by the presence of macropores (Reck et al., 2018; Tang et al., 2019). The results for infiltration indicate an improvement in the quality of soil structure in NR7, mainly in the depth 0–0.1 m. Furthermore, this result promotes good drainage in this reconstructed soil, which is crucial to reduce surface runoff and erosive processes (Reichert et al., 2007; Acton et al., 2011).

The transformations related to bulk density and total porosity in the surface depth of the rebuilt soil could have been accelerated through the action of the tree species *Croton matourensis*, which had the greatest values for abundance in the study areas (Table 4), mainly due to the large amount of litter deposited on the ground, with average values close to those of the reference forest, as reported by Martins et al. (2018) in a study done in NR7.

The soil fertility results showed that in the surface soil layer the NR2 and NR7 systems were not different except for average pH and P and Al concentrations. However, soil fertility in NR2 and NR7 was significantly greater than in FOR, except for P (Table 2). The largest pH values were observed in the natural regeneration systems in depths 0–0.1 and 0.1–0.2 m, which could be attributed to intense deposition of organic matter from the regenerating species, promoting increases in exchangeable base concentrations, as well as to combining soil with different acidity levels by mixing soil horizons from the subsoil with topsoil during the soil reconstruction process.

The results indicate that the increase in pH values is directly associated with a reduction in exchangeable aluminum and an increase in the availability of nutrients in the substrate (Table 2). Ca and Mg concentrations, and consequently the sum of bases, were significantly greater in areas under natural regeneration compared to the reference ecosystem (Table 2).

The results for organic matter show that NR7 had significantly greater contents than NR2, but still below the reference ecosystem, which is most likely a function of litter deposition of tree species in this system. Besides pH, organic matter content could also have contributed to the greater concentrations of Ca, Mg, K, and the sum of bases in NR7 when compared to NR2 and FOR. This is due to the effects of organic matter on cation exchange capacity (CEC) and consequently soil fertility (Liu et al., 2020).

Martins et al. (2018), studying the deposition and concentrations of nutrients in litterfall in NR7, FOR, and a plantation of seedlings of native trees, related that NR7 had the highest rate of litter deposition and concentration and content of nutrients, especially N and K. These authors suggest that *C. matourensis*, which was predominant at NR7, was the species that contributed the most to nutrient transfer to the soil. In this way, the rapid transformations of some physico-hydrological and chemical attributes in the soil surface depth could have been driven by litter deposition from the regenerating trees, thus demonstrating the importance of the natural regeneration method for ecosystem restoration.

3.2. Dominance of vegetation classes

Considering a radius of 10 km from the center of the bauxite mine, the most dominant vegetation group was dense forest, with 145.8 km^2 (46% of the evaluated area), composed of native forest fragments that show signs of past logging activities (Fig. 5). The native forest fragments class in an intermediate stage of succession (secondary forests of about 20 years of age), occupies 42.1 km^2 (13% of the evaluated area). Forest ecosystem shifted into patches highly degraded and/or altered natural ecosystem (forests in initial succession, exposed soil, deforested/burned areas, and agriculture and cattle ranching) occupy a total of 124.4 km^2 (39% of the evaluated area).

The classes Dense forest and Forest in an intermediate stage of succession occupy a total of 187.9 km^2, which is 59% of the evaluated area. These forest fragments, which are within a radius of 10 km of the restoration areas, are important sources of seeds and propagules that can accelerate natural regeneration in the restoration areas (Crouzeilles and Curran, 2016). These results are fundamental for decisions made on the restoration method to use in a degraded area, since the forest matrix at a landscape scale increases the possibility of success of restoration efforts (Alves and Metzger, 2006; Chazdon and Guariguata, 2016).

3.3. Regenerating vegetation

At NR2, species richness, number of families, and abundance were greater in the inferior stratum, compared to the intermediate one, with 2800 and 1566 ind ha^{-1}, respectively (Table 3). The most prevalent regenerating species in this system was *C. matourensis*, with 85.2% of the total of regenerating individuals in the superior strata, 48.5% in the intermediate, and 11.9% in the inferior stratum (Table 4). These results show that in just two years there is already a forest vegetation structure on reconstructed soil after bauxite mining. This can be attributed to resilience driven by the surrounding forest matrix, and also to the seedbank present in the deposited topsoil, which promotes natural regeneration. The topsoil represents the first few centimeters of soil removed before the bauxite extraction, which is generally used in the restoration process to provide a seedbank and nutrients for seedling growth (Macdonald et al., 2015).

At NR7, the abundance was 1096 ind ha^{-1} in the superior stratum, being similar to FOR. The abundance of the intermediate and inferior strata at NR7 were 1873 and 1066 ind ha^{-1} (Table 3). These results indicate rapid construction of forest coverage through the natural regeneration method in seven years.

The greatest abundance value was observed in *C. matourensis* in the superior and intermediate strata at NR7, with 52.6% and 49.5% of the total of regenerating individuals, respectively. This demonstrates the

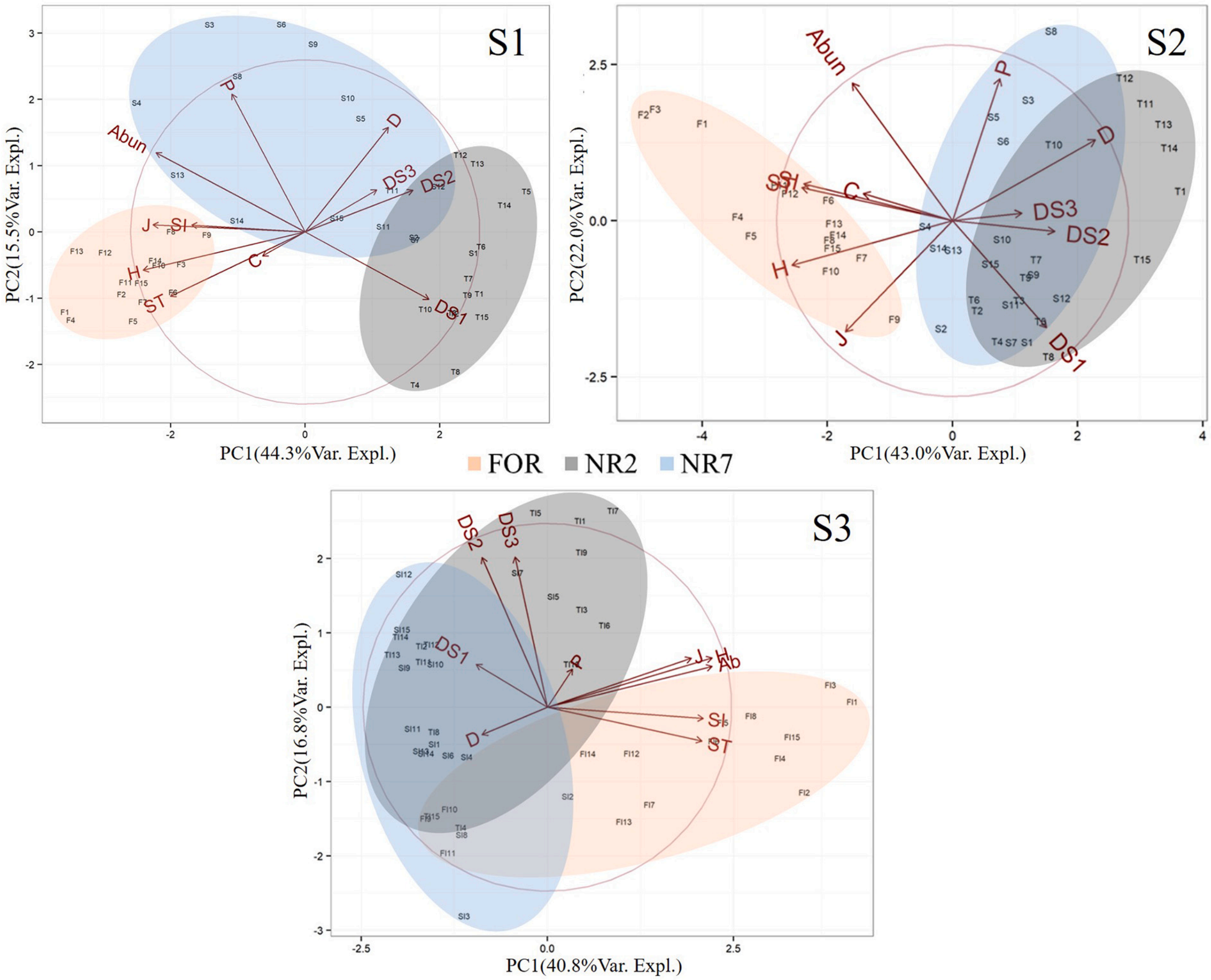


Fig. 6. Principal Components Analysis (PCA) for data from the superior, intermediate, and inferior vegetation strata (S1, S2 and S3) and soil bulk density at depths 0–0.1; 0.1–0.2 and 0.2–0.4 m (DS1, DS2, and DS3) in the natural regeneration of a restoration area after bauxite mining of two (NR2) and seven years (NR7), and in a reference native forest fragment (FOR), eastern Amazon, Brazil. J = Pielou evenness; H = Shannon index; D = Ecological dominance; species abundance: P = Pioneer; SI = Initial secondary; ST = Late secondary, and C = Climax.

importance of this species in the successional process in NR2 and NR7, which has the ecological characteristic of rapid growth and canopy construction. This also indicates rapid reproduction through flower and fruit production during most of the year (Lima and Pirani, 2008), besides a large production of biomass (Lopez et al., 2002), which makes an important contribution to soil coverage. In contrast, the values for the Shannon diversity index were low in NR2 and NR7, indicating low evenness and high ecological dominance. This shows that these sites have low species diversity and are predominantly occupied by many individuals of a few species. These results are expected for areas in the initial stage of ecological succession, which are generally characterized by occupation by only a few pioneer species, a phase that can last from five to ten years, depending on the degree of degradation and/or scarcity of propagules (Chazdon, 2008; Salomão et al., 2012).

Although *C. matourensis* demonstrated a successful ability to colonize areas of natural regeneration, in two years (2015 and 2016), in many NR7 plots, there was synchronous mortality of many individuals of this species in the superior stratum (Fig. 2 – F). Based on the results of physical and chemical attributes of the soil, and the data for the regenerating vegetation, this synchronous mortality may possibly be related to stress caused by the occurrence of ferruginous concretions in the interface between the topsoil and the layer of sterile material. In many places, these concretions can be up to 60% of the 0.3 to 0.5 m depth. This stress may also be a function of the compaction in the subsoil, and of the strong "El Niño" that occurred during this period, which greatly reduced rainfall in the experimental area (Martins et al., 2018; Giuliatti et al., 2019).

Low species diversity and high ecological dominance of just one species makes the ecosystem even more vulnerable. However, further studies are necessary to investigate the issue of synchronous mortality of regenerating vegetation species in this system. It is important to emphasize that no soil movement, such as disking or harrowing, occurred when the soil was replaced on the mined sites before the process of natural regeneration began.

The Principal Components Analysis (PCA), using vegetation and soil density data (Fig. 6), showed an opposite relationship between soil density (DS1, DS2 and DS3) and abundance of regenerating individuals (Abun) in the superior stratum (S1), with DS1, DS2 and DS3 associated with data from plots in NR2, while DS2 and DS3 are associated with most of the plots in NR7. Moreover, Fig. 6 shows that larger abundance values in NR7 were recorded in plots that were further away from plots DS2, DS3, and ecological dominance (D).

In the intermediate stratum (S2) there was a strong association with ecological dominance and soil bulk density in the three depths for the plots in NR2 and NR7. In the inferior stratum (S3) there was a strong association between the variables DS1 and ecological dominance. Most of the plots in NR7 were opposite the variables SI and ST, since 100% of the regenerating species in this stratum were pioneers (Table 4).

Considering that just five species of the pioneer group accounted for 87.7% of the total abundance in the intermediate stratum in NR7, this shows that at 7 years of regeneration there are few individuals of different tree species and relatively poor ecological conditions to establish the process of substitution of the first regenerating pioneers. In this context, the low diversity and high dominance of tree and shrub species could represent a risk for the evolution of forest succession, since a large number of individuals of the same species make the system more susceptible to disturbance (Walker and Del Moral, 2008; Pickett et al., 2008; Brancalion et al., 2015). As an example, the subsoil compaction in NR2 and NR7, and the occurrence of the climatic phenomena El Niño and La Niña, at the study sites between 1989 and 2018 (Giuliatti et al., 2019) may have imparted negative effects on the regeneration due to the low diversity and high dominance of species at these sites.

In this context, the results from this study, coupled with field observations of synchronous mortality of many individuals of regenerating trees and shrubs. Hence, operational procedures such as reshaping and reforesting mined areas become important, especially to break compacted soil layers, using substrate without ferruginous concretions and gravel, or at least with a low concentration of them, in the first few centimeters of the soil, and planting a wide diversity of vegetation species.

In this study, the use of natural regeneration for restoration of mined areas was efficient in stimulating the initial occupation by tree and shrub species that rapidly grow and cover the soil. This method was also successful at establishing good edaphic conditions at the surface, with good results for organic matter, nutrient availability, density, porosity, and soil water infiltration, especially considering the high degree of degradation that strip mining causes to an ecosystem. However, the low diversity and high ecological dominance of a few species with a large number of individuals, coupled with unfavorable environmental conditions, including the presence of layers of concretions and gravel, subsoil compaction, and climate phenomena, can derail the restoration trajectory.

Therefore, these results indicate that the natural regeneration method is a solid alternative for restoration of mined areas in the eastern Amazon, as long as additional procedures are conducted to improve success chances of this process. One possible alternative in this sense would be enrichment planting using a large diversity of regenerating species to provide resilience against adverse environmental conditions. Considering that the successional transition between the initial and intermediate stages lasts from five to ten years (Salomão et al., 2012), species from the initial secondary or late secondary ecological groups are the only ones capable of growing rapidly in a shaded understory during a phase of rapid maturation (Brancalion et al., 2015). It is therefore recommended that enrichment planting be done mainly with initial or late secondary species, with the goal of increasing species diversity and ensuring the successional process.

4. Conclusion

The method of natural regeneration was efficient to occupy and cover the soil by regenerating tree and shrub species, as well as to contribute to recover important surface-depth attributes of the quality of constructed soil, such as organic matter, nutrient availability, density, porosity, and water infiltration in seven years. The regenerating tree and shrub species had low diversity and high dominance of a few pioneer species.

Interventions are recommended to correct the restoration trajectory in order to enable rapid and efficient forest succession, especially the introduction of early and late secondary successional species. These species should be adapted to the conditions of reconstructed soils and able to compete against dominant species to create diversity and ensure successional evolution of the forest ecosystem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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