

Selection of Key Plant Species for the Rehabilitation of Areas with Constructed Soils after Bauxite Mining in the Amazon Region

Jonilton Paschoal¹, Vicente Sousa², Letícia Silva³ and Igor Gonçalves⁴

1. Environment Manager

2. Environment Analyst

4. Forest Engineer

Mineração Paragominas S.A (Hydro Paragominas), Paragominas/PA, Brazil

3. Forest Engineer of Egis - Engenharia e Consultoria Ltda, Cotia-SP, Brazil

Corresponding author: jonilton.paschoal@hydro.com

Abstract

This study selected nine plant species that presented resilient behavior to environments classified as difficult areas for vegetal recovery in constructed soils after bauxite mining, due to low nutrients availability, which are necessary for the plant development. The selected species are native from the amazon biome and are produced in Hydro Paragominas' nursery. Hydro Paragominas is part of the Norsky Hydro group, located at the municipality of Paragominas, state of Pará, North Brazil. In this bauxite mine, forest recovery over mined areas is performed since 2009. The work aims to implement natural mimetics by starting ecological succession in the environment where natural regeneration will be induced, or selected species will be planted. In 2020, by applying literature criteria based on the species ecological group, for the classification of pioneer species through interactive data visualization software product developed by Microsoft, it was possible to select species produced in Hydro Paragominas' nursery. On field observation was held to verify areas rehabilitated from 2009 to 2014, where those species were planted or had grown spontaneously through natural regeneration. Amongst 63 species listed on Power BI, nine pioneer species from the Amazon region, were selected: *Parkia platycephala* Benth, *Inga edulis* Mart, *Inga laurina* (Sw.) Willd, *Inga alba* (Sw.) Willd., *Hymenaea courbaril* L., *Clitoria fairchildiana* R.A. Howard, *Byrsonima verbascifolia* (L.) DC., *Byrsonima crispata* A.Juss., *Cecropia pachystachya* Trécul. This study suggests the larger seedlings production of the nine species selected for the plantation on areas yet to recover, which will help preventing leaching and erosion processes in rehabilitated areas.

Keywords: Mined areas rehabilitation, Pioneer species, Nutrient deficient areas, Bauxite mining, Rehabilitation of degraded areas.

1. Introduction

As humanity evolves with the help of scientific research and technology, geological knowledge advances with discoveries of new mineral deposits. These discoveries have a positive influence on Brazil's economy promoting industrial advance [1]. About 80 minerals are mined in Brazil, attending both domestic and foreign markets [2].

Currently, 11 substances are responsible for 99.7% of the sector production value, as in: aluminum (bauxite), copper, chromium, tin, iron, manganese, niobium, nickel, gold, vanadium, and zinc [1]. The combined production reached the value of 193.5 billion reais in 2020. The Brazilian Aluminum Association - ABAL [3] carried out a survey on the world's consumption of domestic aluminum, founding out a significant increase of 1,583.9 thousand tons; this amount represents a raise in 10.9% compared to 2020 and is now recorded as the largest volume in market research history, since in 1972. Brazil occupies the 4th position among the world's largest producers of bauxite, 3rd position in largest mineral reserve and 3rd place among the largest alumina producers [4]. Besides, Brazil hosts high-quality bauxite deposits [5].

The State of Pará stands out for locating 90% of the bauxite deposits in Brazil (Pinheiro et al. 2016). Paragominas and Juruti are the municipalities that have the largest bauxite deposits in Pará [1].

As much as the mining sector contributes positively to Brazil's economic balance, mining companies are not exempt from legal obligations. Legislation has been improving; for example, mining projects are obliged to submit its Mine Closure Plan during the licensing process, including a rehabilitation plan for degraded area [6].

According to Law No. 6,938 of 1981 that established the National Environmental Policy [7], the interested party is responsible to provide adequate indemnification (when suitable) and to rehabilitate the altered area. Decree No. 97.632/1989 also determines that “*Rehabilitation shall aim the return of the degraded site to a functional form, in accordance with a pre-established plan for land use, to achieve environmental stability*” [8].

Environmental recovery is a multidisciplinary process that aims to achieve excellence and aggregate knowledge in Ecology, Forestry, Soil Science, Economics and Social Sciences, among others [9]. As practices for mined areas rehabilitation, the most used techniques are No-till with fast growing native tree species and Natural Regeneration [10]. The possibility of selecting species, by the no-tillage method of seedlings, is a fundamental factor for ecological restoration practices, which is an enabler for including species from different ecological groups and conservation status [11].

Located in the State of Pará, Brazil, Hydro Paragominas started to execute its Degraded Areas Recovery Plan (PRAD) in 2009, following the guidelines defined on the company's Environmental Impact Assessment (EIA) [12]. Reforestation techniques were resumed in traditional planting and natural regeneration induction, and in 2013 the company started to perform a third technique named as nucleation.

To improve rehabilitation practices, in 2020, a study was conducted aiming to select the most successful species that were found in the rehabilitated areas, focusing on the patches with poor vegetation cover. Species selection is a fundamental factor capable to determine multiples outcomes; in this way, it is important to consider the possibilities of different ecological groups and conservation status [11]. The results are meant to determine in which species the investments in seedling production should be directed, since those species would have high potential to favor the advance of the forest succession process in environments with low availability of nutrients, such as constructed soils after bauxite mining.

2. Experimental

The work was carried out in Paragominas, northeast region of Pará [13], at Hydro Paragominas' site (3° 15' 38"S and 47° 43' 28" W). The soil is characterized by a predominance of Dystrophic Yellow Latosol, medium to very clayey texture, according to the soil classification [13]. The Dystrophic Yellow Latosol are soils of low fertility (naturally), low cation exchange capacity - CTC and low levels of base saturation [15]. In addition, the soil presents high weathering, they are deep, drained soils, with very low natural fertility. It has a subsurface described as a thick horizon B latosol, with low content of easily alterable primary minerals [16].

In 2020, Hydro Paragominas carried out a quality assessment on 1,363.28 ha of rehabilitation areas, whose reforestation techniques were applied between 2009 and 2014. Of this total, using the Normalized Difference Vegetation Index - NDVI in satellite image, were identified 170.79 ha with poor vegetation cover and/or presence of exposed soil [17] (Figures 1 and 2).

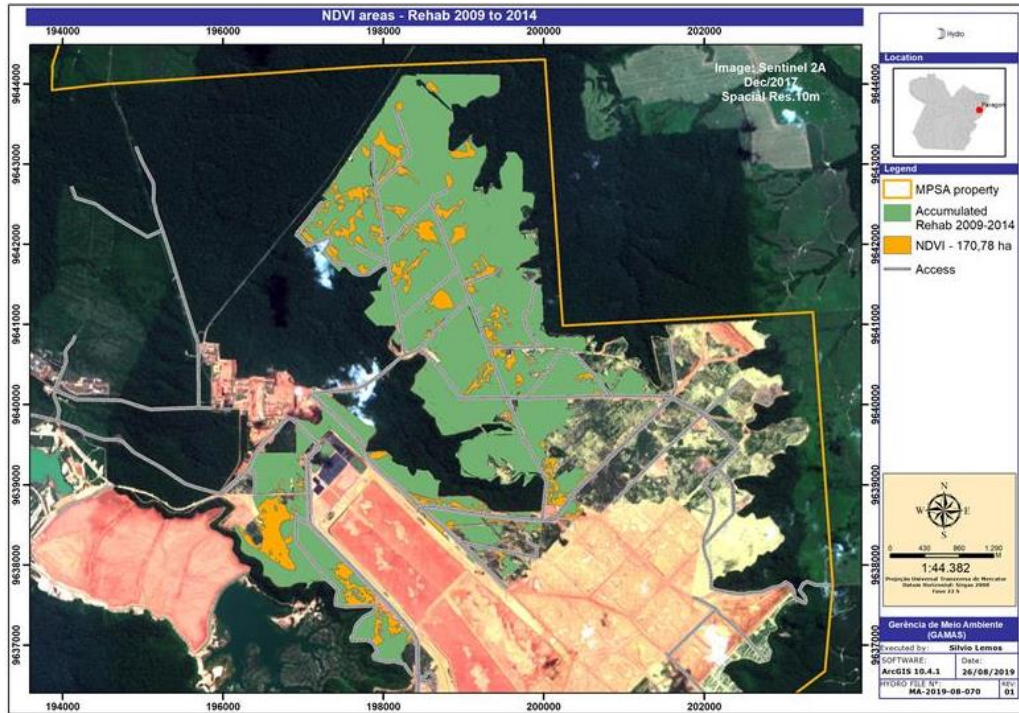


Figure 1. Hydro Paragominas' rehabilitated area (rehab) between 2009 and 2014 in green and areas with poor vegetation cover classified using NDVI.



Figure 2. Hydro Paragominas' nursery (A) and areas undergoing rehabilitation with poor vegetation cover (B).

In order to select species to be used in enrichment plantations in these areas of low vegetation cover, the following procedures were carried out: (1) to list the species produced in the Hydro Paragominas' seedling nurseries; (2) to classify the species produced in the nurseries in ecological groups according to scientific review; and (3) to observe in areas undergoing rehabilitation with poor vegetation cover which of the pioneer species produced in Hydro Paragominas' nurseries have the highest incidence. All data were processed in the Microsoft software PowerBi.

It is important to emphasize that all the species produced in the Hydro Paragominas' nursery are native to the Amazon biome, whose seeds and propagules used in the production of seedlings are collected on the forest patches located at the mine plant. Furthermore, the concept used for focusing on pioneer species was derived from natural mimetics, since this ecological group composes the diversity of the initial forest successional stages. Pioneer species have great adaptive capacity in open areas, are attractive to fauna and have rapid growth [10].

3. Results

In 2020, 63 species were produced in the Hydro Paragominas' nursery (Table 1), by using data classification in PowerBi we got the dashboard presented on Figure 3, which shows the ecological groups, the families, and the scientific names of the species produced.

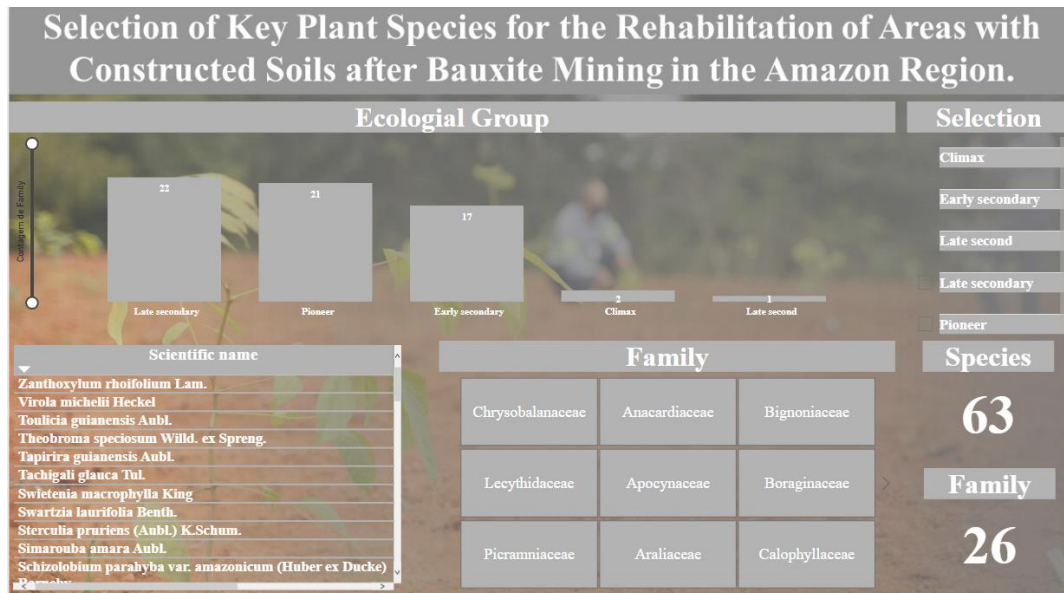


Figure 3. Dashboard the Selection of Key Plant Species for the Rehabilitation of Areas with Constructed Soils after Bauxite Mining in the Amazon Region.

Based on scientific literature review [10; 18; 19; 20], 21 of the 63 species produced in the nursery are classified as pioneer (Figure 4).



Figure 4. Dashboard the Selection of Key Plant Species for the Rehabilitation of Areas with Constructed Soils after Bauxite Mining in the Amazon Region.

After field verification for the incidence of the 21 pioneer species in areas undergoing rehabilitation presenting low vegetation cover, 9 species were selected (Table 1).



Figure 5. Dashboard the Selection of Key Plant Species for the Rehabilitation of Areas with Constructed Soils after Bauxite Mining in the Amazon Region.

The nine selected species were: *Byrsonima crista*, *Byrsonima verbascifolia*, *Cecropia pachystachya*, *Clitoria fairchildiana*, *Hymenaea courbaril*, *Inga alba*, *Inga edulis*, *Inga laurina*, *Parkia platycephala* (Table 1).

Table 1. List of the 63 species produced in Hydro Paragominas' nursery in 2020; from which 21 species were classified as pioneer (in bold) and nine were pioneer species with great incidence on areas undergoing rehabilitation with poor vegetation cover (in bold and italic).

N	Common name	Scientific name	Family	Ecological group
01	Abiu	<i>Pouteria sp.</i>	Sapotaceae	Late secondary
02	Abiu-de-macaco	<i>Chrysophyllum sparsiflorum</i> <i>Klotzsch ex Miq.</i>	Sapotaceae	Late secondary
03	Amapá-doce	<i>Brosimum parinarioides</i> Ducke	Moraceae	Late secondary
04	Andiroba	<i>Carapa guianensis</i> Aubl.	Meliaceae	Early secondary
05	Angelim-pedra	<i>Hymenolobium petraeum</i> Ducke	Fabaceae	Late secondary
06	Cacau-do-mato	<i>Theobroma speciosum</i> Willd. ex Spreng.	Malvaceae	Early secondary
07	Canela-de-jacamim	<i>Rinorea flavescens</i> (Aubl.) Kuntze	Violaceae	Early secondary
08	Capoteiro	<i>Sterculia pruriens</i> (Aubl.) K.Schum.	Malvaceae	Early secondary
09	Copaíba	<i>Copaifera langsdorffii</i> Desf.	Fabaceae	Late secondary
10	Cuia-de-macaco	<i>Couroupita guianensis</i> Aubl	Lecythidaceae	Late secondary
11	Cumarú	<i>Dipteryx odorata</i> (Aubl.) Willd.	Fabaceae	Late secondary

N	Common name	Scientific name	Family	Ecological group
12	Embaúba	<i>Cecropia pachystachya</i> Trécul	<i>Urticaceae</i>	<i>Pioneer</i>
13	Fava-bolota	<i>Parkia platycephala</i> Benth.	<i>Fabaceae</i>	<i>Pioneer</i>
14	Fava-rosa	<i>Cassia grandis</i> L.f.	Fabaceae	Early secondary
15	Fava-tamboril	<i>Enterolobium maximum</i> Ducke	Fabaceae	Early secondary
16	Freijó	<i>Cordia bicolor</i> A.DC.	<i>Boraginaceae</i>	<i>Pioneer</i>
17	Gema-de-ovo	<i>Amphiodon effusus</i> Huber	Fabaceae	Early secondary
18	Gouveira-escamosa	<i>Swartzia laurifolia</i> Benth.	Fabaceae	Late secondary
19	Grão-de-galo	<i>Cordia scabrifolia</i> A.DC.	Boraginaceae	Early secondary
20	Ingá-cipó	<i>Inga edulis</i> Mart.	<i>Fabaceae</i>	<i>Pioneer</i>
21	Ingá-de-macaco	<i>Inga laurina</i> (Sw.) Willd.	<i>Fabaceae</i>	<i>Pioneer</i>
22	Ingarana	<i>Abarema jupunba</i> (Willd.) Britton & Killip	Fabaceae	Late secondary
23	Ingá-vermelho	<i>Inga alba</i> (Sw.) Willd.	<i>Fabaceae</i>	<i>Pioneer</i>
24	Jatobá	<i>Hymenaea courbaril</i> L.	<i>Fabaceae</i>	<i>Pioneer</i>
25	Jenipapo	<i>Genipa americana</i> L.	Rubiaceae	Early secondary
26	João-mole	<i>Guapira opposita</i> . (Vell.) Reitz.	Nyctaginaceae	Late secondary
27	Jupiό-preto	<i>Picramnia sellowii</i> Planch.	Picramniaceae	Early secondary
28	Jutaí	<i>Hymenaea intermedia</i> Ducke	Fabaceae	Climax
29	Louro-preto	<i>Ocotea nigrescens</i> Vicent.	Lauraceae	Late secondary
30	Maçaranduba	<i>Manilkara elata</i> (Allemão ex Miq.) Monach.	Sapotaceae	Late secondary
31	Macucurana	<i>Couepia guianensis</i> subsp. <i>divaricata</i> (Huber) Prance	Chrysobalanaceae	Late second
32	Marupá	<i>Simarouba amara</i> Aubl.	Simaroubaceae	Early secondary
33	Mata-mata	<i>Eschweilera coriacea</i> (DC.) S.A.Mori	Lecythidaceae	Late secondary
34	Mogno	<i>Swietenia macrophylla</i> King	Meliaceae	Late secondary
35	Monguba	<i>Pachira aquatica</i> Aubl.	Malvaceae	Early secondary
36	Morototó	<i>Schefflera morototoni</i> (Aubl.) Maguire, Steyerm. & Frodin	Araliaceae	Late secondary
37	Mucurucá	<i>Toulicia guianensis</i> Aubl.	Sapindaceae	Early secondary
38	Murici-do-campo	<i>Byrsonima verbascifolia</i> (L.) DC.	<i>Malpighiaceae</i>	<i>Pioneer</i>

N	Common name	Scientific name	Family	Ecological group
39	Muruci-da-mata	<i>Byrsonima crisper</i> A.Juss.	<i>Malpighiaceae</i>	<i>Pioneer</i>
40	Mututi	<i>Pterocarpus rohrii</i> Vahl	Fabaceae	Early secondary
41	Olho-de-cabra	<i>Pseudima frutescens</i> (Aubl.) Radlk.	Sapindaceae	<i>Pioneer</i>
42	Paineira	<i>Ceiba samauma</i> (Mart.) K.Schum	Malvaceae	Early secondary
43	Paliteira	<i>Clitoria fairchildiana</i> R.A.Howard	<i>Fabaceae</i>	<i>Pioneer</i>
44	Para-pará	<i>Jacaranda copaia</i> (Aubl.) D.Don	Bignoniaceae	<i>Pioneer</i>
45	Paricá	<i>Schizolobium parahyba</i> var. <i>amazonicum</i> (Huber ex Ducke) Barneby	Fabaceae	Pioneer
46	Pau-amarelo	<i>Euxylophora paraensis</i> Huber	Rutaceae	Late secondary
47	Pau-de-balsa	<i>Ochroma pyramidale</i> (Cav. ex Lam.) Urb.	Malvaceae	Pioneer
48	Pau-de-colher	<i>Lacmellea aculeata</i> (Ducke) Monach.	Apocynaceae	Early secondary
49	Pau-preto	<i>Cenostigma tocaninum</i> Ducke	Fabaceae	Pioneer
50	Pente-de-macaco branco	<i>Apeiba tibourbou</i> Aubl.	Malvaceae	Pioneer
51	Roxinho	<i>Peltogyne venosa</i> (Vahl) Benth.	Fabaceae	Late secondary
52	Sapucaia	<i>Lecythis pisonis</i> Cambess.	Lecythidaceae	Late secondary
53	Sumaúma	<i>Ceiba pentandra</i> (L.) Gaertn.	Malvaceae	Late secondary
54	Tachi-preto	<i>Tachigali glauca</i> Tul.	Fabaceae	Late secondary
55	Tamanqueira	<i>Zanthoxylum rhoifolium</i> Lam.	Rutaceae	Pioneer
56	Tamaquaré	<i>Caraipa densifolia</i> Mart.	Calophyllaceae	Pioneer
57	Tapiririca	<i>Tapirira guianensis</i> Aubl.	Anacardiaceae	Pioneer
58	Taquarí	<i>Mabea speciosa</i> Müll.Arg.	Euphorbiaceae	Pioneer
59	Tauarí-branco	<i>Couratari guianensis</i> Aubl.	Lecythidaceae	Climax
60	Tento	<i>Ormosia paraensis</i> Ducke	Fabaceae	Late secondary
61	Timborana	<i>Pseudopiptadenia psilostachya</i> (DC.) G.P.Lewis & M.P.Lima	Fabaceae	Pioneer
62	Ucuuba	<i>Virola michelii</i> Heckel	Myristicaceae	Early secondary
63	Visgueiro	<i>Parkia pendula</i> (Willd.) Benth. ex Walp.	Fabaceae	Late secondary

According to the results obtained from this study, it was possible to direct the production of seedlings in the nurseries, which will help reducing the amount of seedling mortality in the field. In addition to complementing with other species that will have ecological function in the ecosystem being implemented.

Table 2. List of percentages to the annual production of seedlings.

Description	%	Justification
Key Plant Species	35	Species with higher probability of survival in rustic environments.
Species of diversity	20	Species that have entered rehabilitation areas in more advanced stages to increase species diversity.
Species on the red list	15	To safeguard and multiply the species on the local, regional and global lists of extinction risks.
Herbs and Shrubs	20	Ecological function such as increased diversity, rapid soil cover, availability of organic matter to the environment
Plants for wetlands	10	Species will be produced to be planted in flooded places.

4. Discussion

It was possible to observe that the nine selected species survived in unfavorable environments (areas with intense solar incidence, soils with low availability of macro nutrients, absence of organic matter, high level of compaction, and low water retention). The individuals of those species were seedlings planted during rehabilitation, such as *Parkia platycephala* and *Clitoria fairchildiana*, as well as individuals from natural regeneration, such as *Byrsonima verbascifolia* (Figured 6 and 7).

According to Lorenzo et al. [18], it is important to check which species occur in environments after the different disturbances, to know which path the forest succession is following, and which interventions are necessary. Knowles [19] suggests that the importance of knowing the species occurring in the region, which must be combined with knowledge of the phenology and silviculture of nursery production. For the authors, those are the pillars for the success of a restoration project.



Figure 6. The development of *Byrsonima verbascifolia* (A) and *Parkia platycephala* (B and C) after 4 years in areas with poor vegetation cover.



Figure 7. The development of *Parkia platycephala* (A) and *Clitoria fairchildiana* (B) after 2 years in areas with poor vegetation cover.

For environmental recovery in natural structural soil conditions, applications of environmental restoration techniques are already necessary, this process becomes much more difficult when it is practiced on constructed soils, which have distinct and more challenging characteristics than the natural soils of the region (Dystrophic Yellow Latosol). However, research carried out at Mineração Paragominas resulted that after seven years an area rehabilitated with the Induction of Natural Regeneration technique was similar in terms of physical attributes of the soil (density and total porosity) to the forest soil used as reference [2].

An environment with successful vegetation establishment after mining, even under conditions of diversity and structure different from a nearby native forest [10], can provide an ecologically sound environment, compensating for some momentarily habitat losses, enhancing recolonization, which tends to increase the richness and diversity of fauna components over the years [20].

In 2021 and 2022, Hydro Paragominas' nurseries managed to increase the number of produced seedlings from 63 to 88 species [21], consecutively the selection list of key species for areas of constructed soils after bauxite mining in the region Amazon must grow. Currently, 4 more species are under study: *Bixa orellana*, *Cassia grandis*, *Ceiba pentandra* and *Ochroma pyramidale*.

5. Conclusion

Nine pioneer species were selected as the most adapted in areas undergoing rehabilitation presenting low vegetation cover. These species were able to survive in environments with intense solar incidence, soils with low availability of macro nutrients, absence of organic matter, high level of compaction and low water retention. The software Power BI demonstrated to be an efficient tool to aid data segmentation and analysis.

After an increase of seedling production of the nine selected species, they will be prioritized in enrichment planting activities to improve vegetation coverage in areas undergoing rehabilitation with poor vegetation cover. Hydro Paragominas should continue to apply this species selection method as new species are added in the nurseries derived from field inventories.

Additionally, further analysis can be developed with spontaneous plant species such as the ones identified by previous studies [22], which may help increasing species diversity and longevity on the initial phase of rehabilitation of mined areas.

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