A TWO-PHASE PROCESS FOR REVEGETATION OF ACIDIC BAUXITE TAILINGS IN THE AMAZON REGION, BRAZIL[1]

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Abstract: This paper presents the methodology developed by the association of Mineração Rio do Norte S.A. with Embrapa/Agrobiologia and the Soil Department of Federal University of Viçosa to promote revegetation of tailings ponds from bauxite mining in Porto Trombetas, Para State, Brazil. The tailings have a fine texture (77% clay), are low in nutrients, have low pH (4.5) and high P-fixation capacity. This technology is based upon a two-phase process. In the first phase, seeds of leguminous trees and shrubs, inoculated with N-fixing bacteria and mycorrhizae (VAM fungi), are hydroseeded over the tailings with fertilizer. This initial phase accelerates the tailings drying and incorporates carbon and nutrients into the tailings surface. In the second phase, after substrate consolidation, native secondary and pioneer species are planted with the objective of ensuring more biological diversity and sustainability in the system. Among the evaluated species, *Sesbania virgata*, *S. exasperata*, *Cecrópia sp.*, *Parkia discolor*, *Styphnodendron guinensi*, *Leucaena leucocephala*, *Hidrocoria corumbosa* and *Chamaecrista flexuosa* have been used with success in the first phase, and *Sclerolobium paniculatum, Clitoria farchildian*, *Eugenia* sp., *Tapirira guyanensis*, *Dalbergia spruceana* and *Enterolobium maximum* have been successful in the second phase. Four years after revegetation of the first tailings pond, monitoring results indicate a significant increase of biological activity in the substrate and the presence of different species from natural invasion and regeneration, indicating that primary successional processes are active. These results indicate that the two-phase revegetation process may be more appropriate for the tailings ponds in Porto Trombetas than conventional reclamation practices.

Additional Key Words: P-fixation, vesicular arbuscular mycorrhizae, leguminous trees.

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Introduction

Porto Trombetas is located in Para State, in the northern Brazilian Amazonia. According to the classification of Koppen, the area has climate type AF1. The annual rainfall varies from 2500 to 3000 mm. The site is characterized as humid tropical climate, with an annual median index of relative humidity above 75%, and only two months with an average around 70%. There are two periods of differing precipitation: a rainy season (December to May) with an average of 265.8 mm/month and a dry season (July to October) with an average of 72.3 mm/month. The annual median temperature was 25.7 °C between 1971 and 1994.

The mining operations started in 1979, and in the same year, the company shipped its first Brazilian bauxite cargo to Canada. The ore body underlies an 8-meter thick overburden covered by dense vegetation. Brush removal and overburden stripping are required prior to mining which progresses sequentially down adjacent linear strip pits, and topsoil is deposited over the nearest previously mined out strip.

The ore concentration involves granulometric reduction, washing, and final classification, which generates tailing refuse. Between 1979 and 1984, the tailings were dumped into the Igarapé Caranã, a stream that drains to Batata Lake, a natural lake alongside the Trombetas River, a tributary of the Amazon River. During the period from 1984 to 1989, the Company deposited the tailings directly into Batata Lake by a piping system. From 1979 to 1989, around 24 millions tons of solid materials were deposited into this lake, which caused severe impacts to 30% of its surface, about 630 ha (Lapa, 2000). Since 1990, tailings have been deposited into special reservoirs built in the mining areas (Fig. 1).

The initial tailings are returned as a mud with 7% solids (primarily clay sized), dominated by kaolinite (47%), Al-oxides (21%) and Fe-oxides (21%). During the natural drying process, the kaolinite clays tend to initially crack (Fig. 2) and compact and form a high-density substrate, with no structure or macropores (other than large cracks). The lack of organic matter intensifies these physical problems.

With respect to chemical properties, the refuse has low pH and nutrient content (Table 1), which when coupled with the negative physical characteristics, forms a very unfavorable scenario for plant establishment and growth. These initial properties emphasize the importance of appropriate fertilization for revegetation. However, fertilization alone is not enough, since inputs of organic carbon are also needed to improve the physical characteristic of the substrate and to allow sucessional processes to provide for sustainability of the revegetation systems.

Figure 1. General view of the bauxite tailing impoundments before and after the revegetation in Porto Trombetas, Para State, Brazil.

Figure 2. Planting in the substratum Cracks with seedlings of *Cecropia sp.* Note dense massive nature of consolidated tailings.

Table 1. Physical and chemical characteristics of the bauxite refuse.

Clay	Silt	Sand	O.M.	N	P	K	Al^{3+}	Ca^{2+}	Mg^{2+}	H+Al	pH
------------------ % ----------------					mg kg^{-1}		------------- $cmol_c$ kg^{-1} --------				
77	22	1	0.02	0	0.1	1.0	0	0.05	0.00	1.30	4.9

Revegetation of Tailings Impoundments

Due to local climate and characteristics of the refuse and the tailings deposition process, the material takes more than two years to consolidate and to allow movements of workers or machines onto it. With the objective of accelerating the dewatering process, and at the same time improving substrate quality by adding carbon and nutrients, different tests were carried out to develop a methodology to accelerate the initiation of revegetation.

Research conducted between1994 to 1998 resulted in a revegetation methodology based on a two-phase process. In the first phase, seeds of trees and shrubs of leguminous species, inoculated with selected strains of *Rhizobium* bacteria (Faria *et al.* 2002) and vesicular arbuscular mycorrhizal (VAM) fungi (Franco *et al.* 1997) are hydroseeded over the impoundments. During this phase, we used fast growing and high humidity tolerant species to add carbon to the substrate and to accelerate its drying. The manual planting of locally adapted native species is the predominant approach used in the second phase.

The first phase procedures are similar to the "green carpet" approach (Griffith et al., 1996) in which a high amount of seed was used to promote a quick substrate cover. The critical aspect of the hydroseeding approach, which required different experiments to elucidate, was to establish the adequate number of seeds required for each species. The final plant density is very important because we need a minimum value to promote rapid substrate cover, high evapotranspiration (to dry the substrate) and carbon fixation, without promoting a high level of competition among species and associated plant establishment problems. In the same way, research on the form and required amounts of fertilizers, species selection, and adjustments of the hydroseeding equipment was also performed over an extended period by the research team and the environmental technicians of the company.

Presently, the hydroseeding process is carried out with 35-42 kg/ha of seed from seventeen species. *Sesbania virgata*[1], *S. exasperata*[2], *Senna occidentalis*[3], *Senna reticulata*[1] *Senna sp*[2] *and Acosmium nitens*[1] forming the base of the process with 60% of the total seed. The remaining 40% is represented by species like *Chamaecrista flexuosa*[2], *Acacia holosericea*[4], *Cecropia sp*[1], *Leucaena leucocephala*[5], *Sclerolobium paniculatum*[1], *Parkia discolor*[1], *Styphnodendron guianensis*[1], *Aeschynomene sensitiva*[2] and *Hidrochorea corymbosa*[1].

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[1]Brazilian native tree species; Brazilian native shrub species; [3] Annual herbaceous Brazilian native species; [4]Exotic tree; [5] Exotic shrub

With plant growth and associated increased evapotranspiration, the tailings substrate dries out more quickly. Because part of the species utilized are annual shrubs, we have observed a natural process of plant mortality during the later portion of the drying process. This is very important because these plants are "doing their job" by adding carbon and nutrients (mainly nitrogen by N-fixing bacteria) and creating favorable physico-chemical conditions for subsequent sucessional processes. One year following hydrosseding, the tailings solidification occurs sufficiently to allow the start of the second phase of the revegetation process, which we call "enrichment".

In the second phase, the planting is accomplished by taking advantage of the substratum cracks that formed during initial drying, since the high substratum bulk density of the polygon masses does not readily allow the opening of planting holes. The polygonal drying cracks then become holes for planting where the superficial layer of the stored soil and fertilizers are deposited and seedlings are planted (Fig. 2). The species used in this phase are native trees and in terms the sucessional status, most of them are pioneers. The seeds of N_2-fixing species are inoculated with selected strains of bacteria. Some species used during the "enrichment" phase are: *Clitoria fairchildiana, Inga heterophylla, Campsiandra comosa* var. *laurifolia, Acosmiun nitens, Dalbergia inundata, Cecropia sp., Dalbergia spruciana, Parkia discolor, Copaiferamultijuga, Euterpe oleracea, Catostema albuquerquei, Sclerolobium paniculatum, Enterolobium maximum, Genipa americana, Senna multijuga, Tapirira guianensis, Tabebuia barbata, Eugenia cumine,* and *Mabea caudate.* These species were also used to revegetate the research impoundment, but the number of species may change in subsequent impoundments according to the availability of the various seedlings.

Over the last ten years, we also carried out field investigations to identify species tolerant to the unfavorable characteristics of the substratum. These investigations resulted in a significant increase the number of species used in the revegetation program of the company, and have greatly improved our collective knowledge of local vegetation biodiversity. Through 2006, we collected more than 800 legume species. Among them, 184 species possessed the capacity to associate with N_2-fixing bacteria (65 *Mimosoideae,* 45 *Caesalpinoideae,* and 74 *Papilionoideae*).

New Experiments

Today, the primary remaining challenge is to determine the correct amount of fertilizer to ensure a biomass comparable to the surrounding native forest. Two experiments are being carried out with the native species used in the enrichment phase. In both experiments, the plants were subjected to different doses of lime and mixtures of P, K, Ca, Mg, S and micronutrient fertilizers (Table 2). Twenty-eight and forty-eight months after planting, we evaluated the height and diameter at the base of the stem of twelve species. All species showed positive response to fertilization, but with differing intensity. Figure 2 shows the fertilization effect on the average values of collar diameter and height of the plants.

Comparing the legume vs. non-legume species response to fertilization effects, it is clear that N is the greatest limitation to plant growth on the tailings (Figs. 3 and 4). Considering the growth increment of legume species between 28 and 48 months after planting, there probably exists another type of limitation at the highest levels of fertilization (Figs. 5 and 6).

Table 2. Amount of lime and fertilizers applied to each treatment in the experiment on nutrients and lime levels.

Treatment	Dolomitic lime		Termophosfate‡		K_2SO_4		Micronutrients†	
	kg ha^{-1}	g $plant^{-1}$	kg ha^{-1}	g $plant^{-1}$	kg ha^{-1}	g $plant^{-1}$	kg ha^{-1}	g $plant^{-1}$
1	300	180	200	120	200	120	75	45
2	600	360	400	240	300	180	100	60
3	1.200	720	800	480	400	240	125	75
4	2.400	1.440	1.600	960	500	300	150	90

‡ P-fertilizer obtained by thermal treatment of rock phosphate with silicate and magnesium, containing 14% of P_2O_5 (2% citric acid-soluble) and 7% of Mg.
† 1.8% of B, 0.8% of Cu, 3.0% of Fe, 3.0% of Mn, 0,1% of Mo, and 9.0% of Zn.

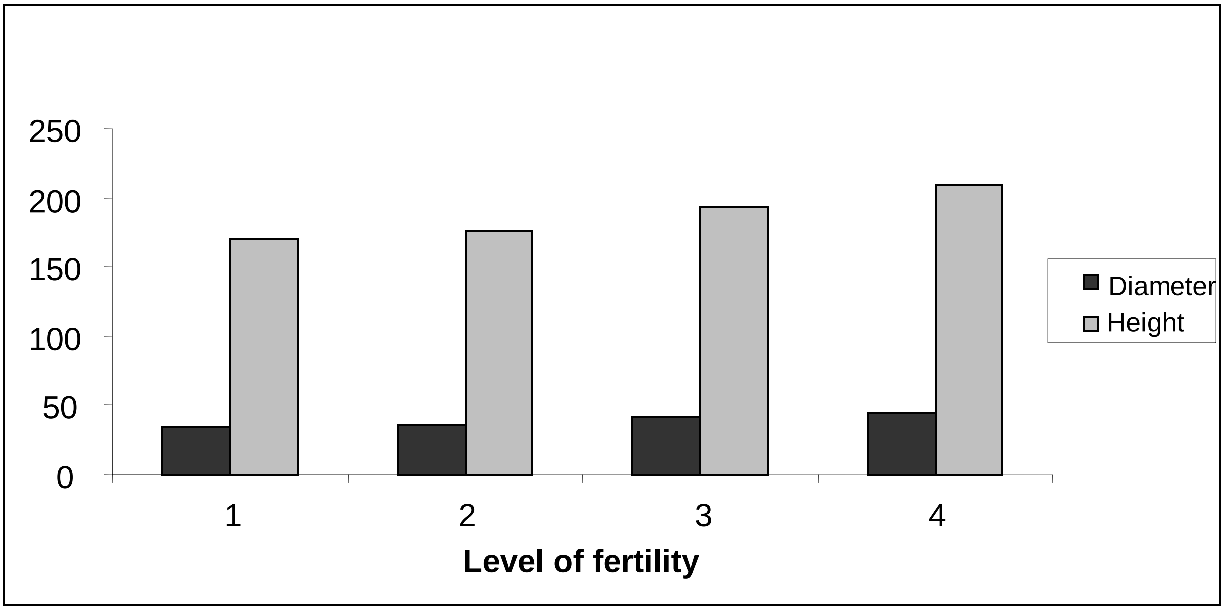

Figure 2. Effect of fertilization levels on average values of collar (mm) and height (cm) of plants from twelve species 48 months after planting.

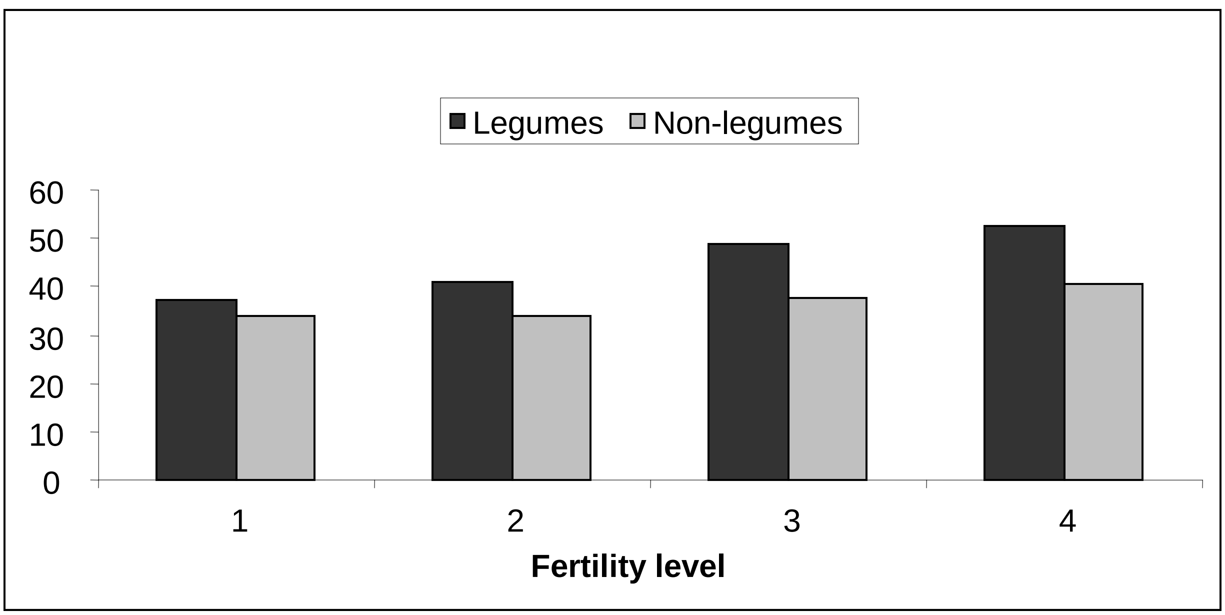

Figure 3. Effect of fertilization levels on average collar (mm) values of plants from legumes and non-legumes species 48 months after planting.

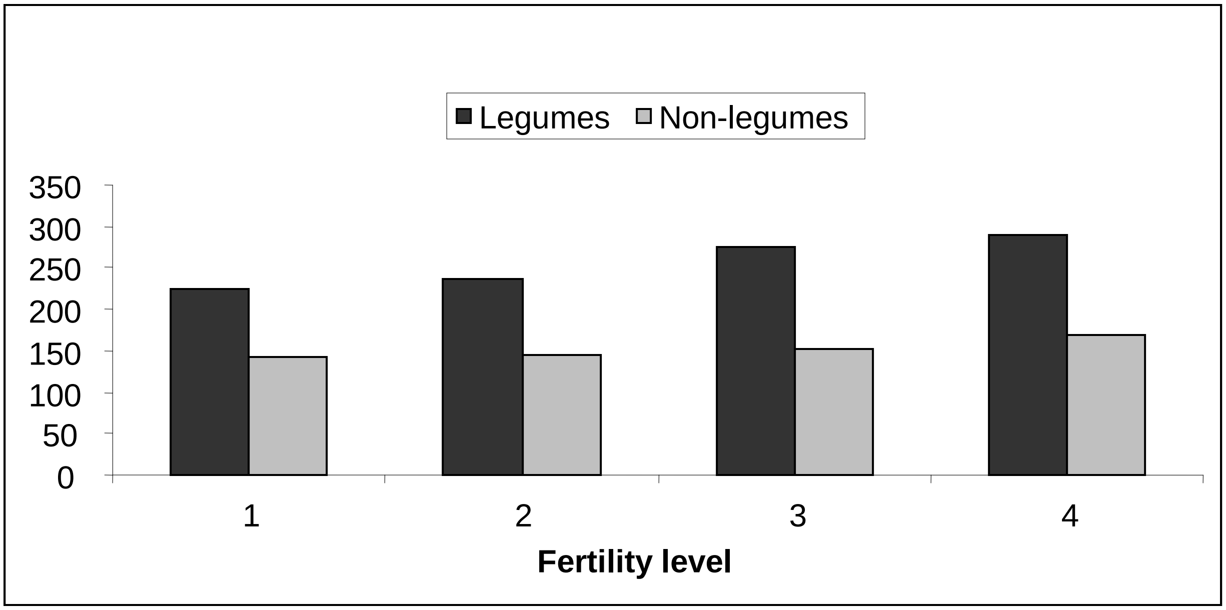

Figure 4. Effect of fertilization levels on average height (cm) values of legumes and non-legumes species, 48 months after planting.

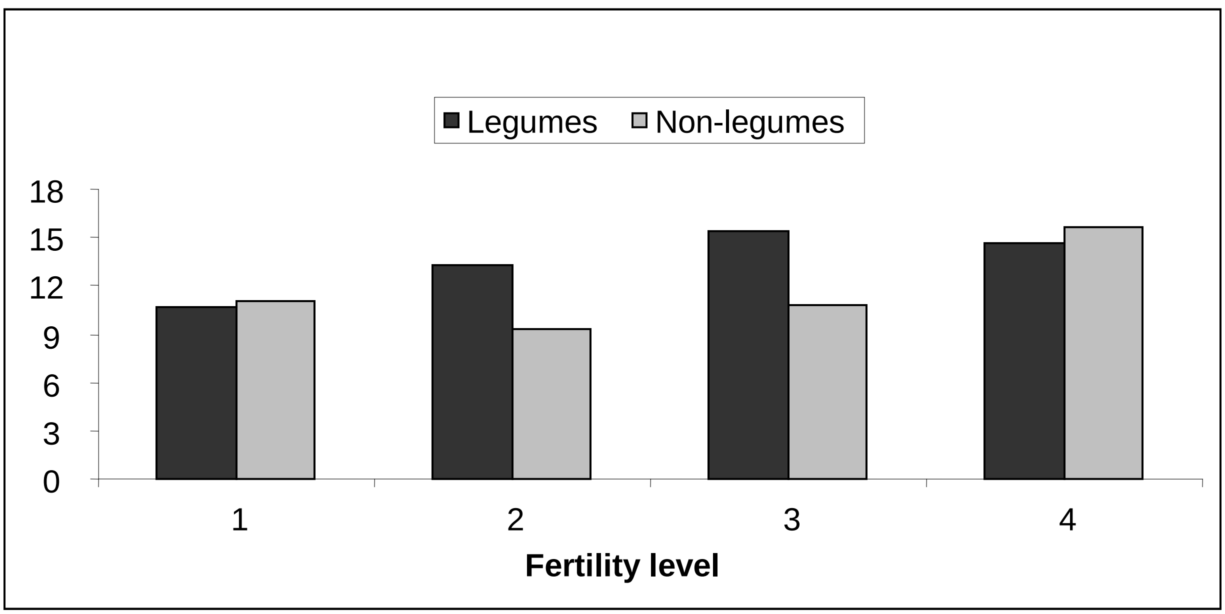

Figure 5. Effect of fertilization levels on average increment values of collar (mm), between 28 and 48 months after planting, to legumes and non-legumes species.

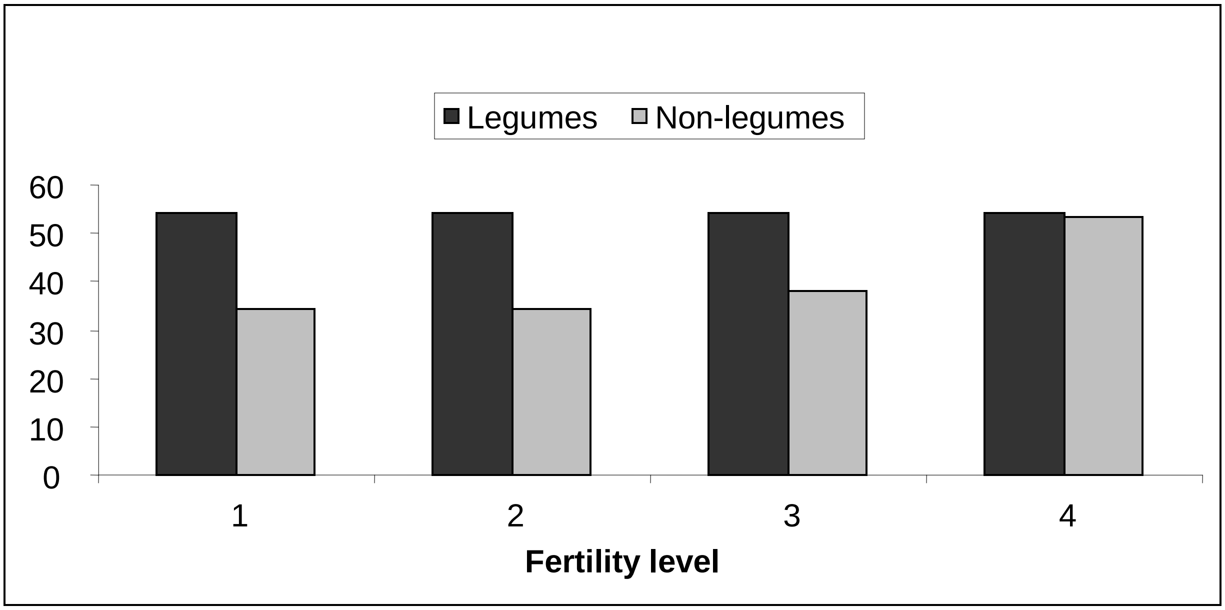

Figure 6. Effect of fertilization levels on average increment values of height (cm), between 28 and 48 months after planting, to legumes and non-legumes species.

Monitoring the Impoundments

Tailings impoundments represent a true "time zero" for soil and plant development (Richmond, 2000), and at the same time, present a special opportunity to study the transformation of a given substrate into a soil. To evaluate this process we are using different chemical, physical and biological soil quality indicators. The monitoring program established by the mining company also evaluates sucessional vegetation processes through the identification and cataloguing of the invasion of local species into the impoundments. To date, these data indicate that soil fauna and biomass, as well as the microbial activity, are positively correlated with the both density and diversity of plants in the reclaimed areas. These soil biotic indicators appear to be more sensitive to productivity recovery then either soil or plant nutrient content.

When considering the improved substratum fertility, it is important to point out that despite the fact that all fertilization was applied to individual plants, we observed a significant increase of organic matter and certain nutrients (e.g. Ca+Mg, N, P and K) 48 months after planting (Table 3).

Table 3. Chemical characteristics of the substratum at different fertility level plots, 48 months after planting. (Average values from three sampling and four replications).

Fertility level	**pH**	**Al^{3+}**	**Ca + Mg**	**P**	**K**	**OM**	**N**
		$cmol_c\ kg^{-1}$		mg kg^{-1}		g kg^{-1}	
1	4.94	0.00	0.92	0.50	4.83	0.21	0.02
2	5.07	0.00	0.53	1.17	5.08	0.29	0.04
3	5.16	0.00	0.64	2.00	7.75	0.36	0.06
4	5.25	0.00	0.71	25.75	8.83	0.36	0.04

Natural Regeneration

Figure 7 presents the percentile distribution of different invasion mechanisms of the species into the area of tailings ponds. In spite of the relative isolation of the area, we verified that half of the diversity of present species in the impoundments arrived through the dispersion of seeds. Considering that most of these species represent zoochoric dispersion, this emphasizes the importance of the fauna (birds, mammals, bats, ants, etc.) in increasing of the vegetative diversity on the impoundments, even in these conditions of extreme disturbance. The physical barriers, however, seem not to impede seed arrival into the area, what suggests dispersal agents performing over long distances such as birds and bats.

We found 78 vegetation species, distributed across 29 botanical families. The families represented by the largest numbers of species were Leguminosae - Mimosoideae with 12 species, Leguminosae-Caesalpinoideae with 11, Leguminosae-Papilionoideae with five, and Myrtaceae with four species. Among the other families, it is important to separate out those with fruiting species such as: Myrtaceae, Crysobalanaceae, Palmaceae, Simarubaceae, Anonaceae and Cecropiaceae. This indicates the importance of introduction of attractive species for fauna that will facilitate natural regeneration (in the case of the planted species) and the arrival of seeds to other areas through the dispersion by those fauna (in the case of the no planted species).

We also verified that a significant portion of the total diversity of species was introduced into the area through planting seedlings and manual spreading of seeds, together adding 40%. These results confirm the success of the revegetation methodology based on the introduction of vegetation biomass through the hydroseeding, fertilization and start of the diversity through the planting for seedlings, and manual release of seeds. In other words, the hydroseeding practice is not designed to generate great initial diversity in the recovering environment, but it does establish a few species with great capacity for biomass production and contribution of organic matter. Subsequently, diversity is stimulated through the planting of seedlings and manual release of seeds, which is further reinforced by natural regeneration. On the other hand, as described by Griffith et al. (1996), this approach was used in this area as a two-phase revegetation strategy, where the natural vegetation succession also carries out indispensable functions.

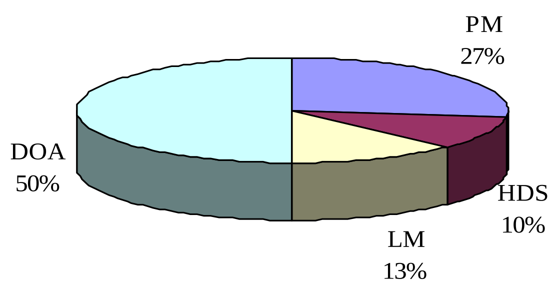

Figure 7. Distribution of the total of sampled species for the different arrival forms in the area. PM – planted as seedlings; LM - manual release of seeds; HDS - hydroseeding; and DOA - dispersion from other areas.

Conclusions

The two-phased approach to revegetation of bauxite tailings impoundments at Porto Trombetas in the Brazilian Amazon Region, has shown to be an appropriate and effective technology considering the adverse physical and chemical characteristics of the substratum and the necessity of promoting rapid drying and a rapid living cover over the substratum. The experiments to date highlight the importance of adding lime and fertilizers in adequate amounts to obtain biomass equivalent to the neighboring forest. The different soil quality indicators used in new monitoring efforts are important to evaluate substratum/soil transformations and associated vegetation sucessional processes in the tailing impoundments.

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References

Faria, S. M., Nara, M., Lima, H. C. 2002. Ocorrência de leguminosas fixadoras de nitrogênio na região de Porto Trombetas, Oriximiná, Pará Brasil In: 53 Congresso Nacional de Botânica, 2002, Recife. Anais do 53 Congresso Nacional de Botânica. Recife PE: Universidade Federal de Pernambuco p.266 – 2.

Franco, A. A, Campello, E. F. C, Dias, L. E., Faria, S. M. 1997. The use of nodulated and mycorrhizal legume trees for land reclamation in mining sites **In:** Biological Nitrogen Fixation for the 21 st Century ed. Dordrecht : Klumer Academic Publ., p. 623-624.

Griffith, J. J.; Dias, L. E. & Jucksch, I. 1996. Rehabilitation of Mine Sites in Brazil Using Native Vegetation. In: *Forests - A Global Perspective*. Majumdar, S.K., Miller, W. E & Brenner, F.J. (Eds.). The Pennsylvania Academy of Science. Philadelphia, Pennsylvania, USA. (Cap. 31) p. 470-488.

Lapa, R. P. 2000. A bauxite e o rejeito da bauxite. In: Bozelli, Esteves, F.A. e Roland, F. (Eds.) Lago Batata. Impacto e recuperação de um ecossistema amazônico. IB-UFRJ/SBL. Rio de Janeiro. (Cap. 3) p. 25-36.

Richmond, T. C. 2000. The revegetation of metalliferous tailings. In: Barnhisel, R. I., Darmody, R. G., and Daniels, W. L. (Eds.) Reclamation of Drastically Disturbed Lands. Agronomy Monograph no. 41. SSSA, Madison, p. 801-818.