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ARTICLE

Influence of Environmental Variables on the Natural Regeneration of a Forest under Restoration after Bauxite Mining and in a Reference Ecosystem in Southeastern Brazil

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ABSTRACT

The shrub-tree floristic composition of the natural regeneration stratum of a bauxite mine in the process of restoration and in a reference ecosystem (remnant of a preserved secondary Seasonal Semi-Deciduous Forest) were analysed to evaluate forest restoration conditions after five years of planting. The influence of canopy openness, accumulated leaf litter and soil attributes in the regeneration stratum were also investigated in both the forests. The floristic composition of the regeneration stratum in the forest under restoration (16 species and 5,083 individuals ha-1) and in the reference ecosystem (58 species and 26,250 individuals ha-1) are distinct due to the difference in the environmental variables. Results showed that the reference ecosystem favours the presence of species that tolerate environments with greater shading and higher aluminium and organic matter content in the soil like *Psychotria carthagenensis* Jacq., while the forest under restoration favours the presence of species adapted to fertile soils and those that tolerate greater luminosity like *Vernonanthura phosphorica* (Vell.) H.Rob.

1. Introduction

The Atlantic Forest Biome in Brazil is considered one of the biodiversity hotspots of the world due to its great diversity of species with a high degree of endemism, and it is a priority area for conservation [1]. The Atlantic Forest region is home to about 60% of the Brazilian population [2] and is responsible for approximately 70% of the Brazilian gross domestic product (GDP) [3,4]. In the state of Minas Gerais, the domain of the Atlantic Forest originally corresponded to 47% of the area of the state, but today this is reduced to 5,4% [5].

The causes of the reduction and degradation of forest areas in Brazil are diverse and include deforestation for timber extraction, expansion of agricultural and livestock activities, real estate expansion and mining. Given this situation, forest restoration has been widely advocated in recent times [6], with the aim of renewing of ecological processes and structures of degraded and fragmented ecosystems [7]. Such restoration activities are mainly focused in mining areas where the entire ecosystem is significantly affected [8].

Bauxite mineral extraction requires suppression of vegetation and removal of soil surface horizons [9,10]. To

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mitigate this, certain compensatory measures must be adopted. In this scenario, in addition to environmental compensation in areas close to the mined site, restoration of degraded ecosystem is required. This approach for restoration aims to create sustainable communities varying stages of ecological succession, representing the diversity and composition of the phytophysiognomy of the reference ecosystem where the degraded or altered area is to be restored [11-13].

In order for a forest restoration project to succeed, an assessment of the forest under restoration through indicators or environmental variables is of utmost importance [14]. These indicators allow to define if the restoration project needs interference or redirection and allow determination of the stage at which the restored forest becomes independent of management interference, i.e. when it shows signs of being self-sustaining [15]. The most commonly used evaluation indicators for a forest under restoration are soil seed bank, seed rain, natural regeneration, canopy openness, and leaf litter production [16,17,18].

Studying floristic and natural regeneration structures is important for understanding the dynamics of a community, the knowledge of local species ecology and for providing insights on the direction that the ecosystem is heading in relation to ecological succession [19]. Such, knowledge of natural regeneration contributes to the improvement of restoration practices [16] and to decision-making regarding possible interventions, such as forest enrichment with species that are important for ecological succession and the elimination of non-native species [20].

Combined with the understanding of community dynamics through the study of the natural regeneration stratum, the knowledge of environmental variables that can influence the composition and trajectory of this stratum is important to understand the distribution and development of species [21].

Thus, the aim of our study was to evaluate the shrub-tree floristic composition of the natural regeneration stratum in a forest under restoration and a reference ecosystem and to make a comparison between the two compositions. Additional aims include characterizing environmental variables (e.g., soil attributes, canopy openness and accumulated litter) and verify the influences of these on the natural regeneration of both forests.

2. Materials and Methods

2.1 Study Area

The study was carried out in a forest under restoration after bauxite mining (A1 forest) and in a preserved forest remnant representing a reference ecosystem (A2 forest). Both forests are located in the municipality of São Sebastião da Vargem Alegre (21°04′20″S and 42°38′11″W), State of Minas Gerais, southeast Brazil, with local altitude varying from 792 to 832 m (Figure 1). In the surrounding area of these forests, there are pasture, preserved forest remnants, eucalyptus plantations and areas in the process of mining.

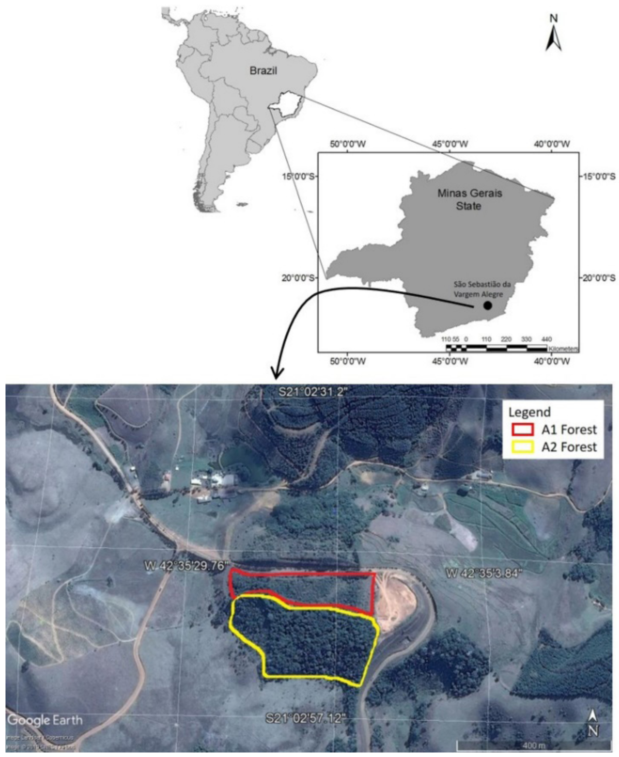

Figure 1. Location of the study area (highlighted). São Sebastião da Vargem Alegre, Minas Gerais, Brazil. A1 Forest: area under restoration; A2 Forest: reference ecosystem. Image source: Google Earth (2019)

The climate of the region is type Cwa according to Köppen classification: humid subtropical climate, with dry winter and hot summer [22]. The annual average minimum temperature is of 18.2 °C and the maximum annual average of 31 °C, with an annual average temperature of 23.5 °C and an annual average rainfall of 1,564 mm [23]. The typical vegetation of the region is classified as Seasonal Semi-Deciduous Montane Forest, belonging to the Atlantic Forest Domain [24].

In A1 forest, bauxite was extracted from a 2.18 ha area in 2008 by the Companhia Brasileira de Alumínio (CBA company). Restoration was subsequently carried out, beginning with topographical recomposition, followed by replacement of the fertile topsoil (soil to 0.3 m depth was removed and stored prior to mining), correction of soil acidity and phosphate fertilization, base fertilization, heterogeneous planting of tree species with spacing of 3.0 m

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× 2.0 m, and finally topsoil fertilization around the planted seedlings. Restoration activities were completed in 2010. The study of natural regeneration was carried out after five years of the beginning of the restoration process.

A2 forest comprises of a 5.30 ha remnant of a preserved secondary Seasonal Semi-Deciduous Forest embedded in the Atlantic Forest Biome, adjacent to the A1 forest, which is in an intermediate stage of succession. This served as a reference ecosystem, assisting in the evaluation of A1 forest.

2.2 Characterization of vegetation

Thirty plots of 2.0 × 2.0 m in both A1 forest and A2 forest were distributed in six rows of five plots, with 5 m between each plot in a row, and with 40 m between rows. For the analysis of natural regeneration, all shrubs and trees with height ≥ 0.30 m and diameter at breast height (DBH = 1.30 m) ≤ 5.0 cm were identified, and their height and diameter at ground level (DGL) were measured.

For unidentified species in the field, botanical samples were collected for later comparison with samples deposited in the Herbarium of the Federal University of Viçosa, MG so as to consult with specialists. Species were classified into families, with their scientific names and respective authors updated according to the system of Angiosperm Phylogeny Group IV [25] and by the database of Species List of Brazilian Flora (http://floradobrasil.jbrj.gov.br/).

The structural characterization of shrubs and trees of the regeneration stratum was carried out by calculating the following phytosociological parameters: dominance, density and frequency [26].

2.3 Environmental Variables

Soil chemical analysis (pH, P, K, phosphorus remnant, bases saturation index, aluminium saturation index, effective cation exchange capacity, cation exchange capacity at pH 7.0, Ca^{+2}, Mg^{+2}, Al^{+3}, potential acidity, and sum of exchangeable bases) and organic matter content analysis were performed. For this, a surface sample of 0-20 cm depth was collected in each of the 30 plots of the A1 forest restoration forest; these were then mixed to form a composite sample. The same procedure was performed in the A2 forest reference ecosystem. Afterwards, the two composite samples from both forests were sent to the Soil Analysis Laboratory of the Department of Soils in the Federal University of Viçosa. The results of soil chemical and soil organic matter analyzes were interpreted according to the references proposed by [27].

Canopy openness was determined by digital hemispherical photography in the centre of each portion of the forests, obtained with an 8 mm lens, which provides a field of view of 180°. The lens was coupled to a digital camera and mounted on an adjustable tripod head with bubble level to stabilize the camera. The photographs were then processed in the Gap Light Analyzer 2.0 software [28].

For the analysis of accumulated litter, a 0.50 × 0.50 m (0.25 m^2) wood template was used in the centre of each of the 60 plots (30 plots in A1 forest and 30 plots in A2 forest) for collecting all the non-decomposed organic material (leaves, branches, fruits and flowers) within the template. This material was later packed in plastic bags, identified and taken to the Forest Restoration Laboratory of the Federal University of Viçosa, MG, where it was transferred to paper bags tagged with identification information for each plot and placed in an oven at 70 °C for 72 h. After drying, the material was weighed in precision analytical scales to obtain dry mass in grams.

2.4 Statistical Analysis

The mean values of species density and species richness obtained in the A1 forest were compared with the A2 forest using Student's t-test for independent samples (with $p < 0.05$ considered to be significant).

The Canonical Correspondence Analysis (CCA) [29] was used to infer the influence of environmental variables on the species distribution for the set of 60 plots. Environmental variables (canopy openness, accumulated litter and soil attributes - pH, P, K, Ca, Mg, organic matter, aluminium saturation index, and bases saturation index) and frequency values for 70 species (number of species present in both forests) were used for the calculations. Species with no significant scores on both axes were removed for the more robust analysis. Thus, the number of species was reduced to 25. The correlations between the species axes and the environmental variables' axes were tested using the Monte Carlo test to estimate the significance of correlations between canonical axes.

3. Results

3.1 Floristic Composition

Sixteen species belonging to 12 families with 61 individuals in total, or 5,083 individuals ha^{-1}, were represented in the A1 forest under restoration. Of these, 54% were trees and 46% were shrubs (Table 1). In the A2 forest reference ecosystem, 58 species were represented, belonging to 26 families with a total of 315 individuals, or 26,250 individuals ha^{-1}. Of these individuals, 79% were trees, 20% were shrubs, 0.7% were palms and 0.3% were not characterized (Table 2).

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Table 1. Phytosociology of the natural regeneration species of A1 forest (Forest under restoration). NI: Number of individuals; IV: Importance value (relative density + relative frequency + relative dominance); SC: Successional category (P: Pioneer, ES: Early secondary, LS: Late secondary); DS: Dispersal syndrome (Ane: anemochory; Zoo: zoochory; Auto: autochory); Hb: Habit (T: Tree, S: Shrub); U: Uncharacterized

Botanical Family / Specie	NI	IV (%)	SC	DS	Hb
Apocynaceae					
Tabernaemontana laeta Mart.	1	2.73	P	Zoo	T
Asteraceae					
Baccharis dracunculifolia DC.	1	1.41	P	Ane	S
Vernonanthura phosphorica (Vell.) H.Rob.	20	47.87	P	Ane	S
Cannabaceae					
Trema micrantha (L.) Blume	1	3.65	P	Zoo	T
Euphorbiaceae					
Alchornea triplinervia (Spreng.) Müll. Arg.	1	1.54	P	Zoo	T
Fabaceae					
Apuleia leiocarpa (Vogel.) J.F.Macbr	2	3.88	LS	Ane	T
Leucaena leucocephala (Lam.) de Wit	13	12.46	P	U	T
Malvaceae					
Triumfetta rhomboidea Jacq.	1	1.47	P	U	S
Melastomataceae					
Clidemia hirta (L.) D.Don	5	5.42	P	Zoo	S
Myrtaceae					
Myrcia splendens (Sw.) DC.	3	4.26	ES	Zoo	T
Primulaceae					
Myrsine coriaceae (Sw.) R.Br. ex Roem. & Schult.	2	2.88	ES	Zoo	T
Solanaceae					
Solanum mauritianum Scop.	5	4.57	P	Zoo	T
Solanum swartzianum Roem. & Schult.	2	1.98	P	Zoo	T
Vassobia breviflora (Sendtn.) Hunz.	1	1.45	P	Zoo	T
Urticaceae					
Cecopia hololeuca Miq.	2	2.94	P	Zoo	T
Verbenaceae					
Lantana camara L.	1	1.49	P	Zoo	S
Total	61				

Table 2. Phytosociology of the natural regeneration species of A2 forest (Reference ecosystem). NI: Number of individuals; IV: Importance value (relative density + relative frequency + relative dominance); SC: Successional category (P: Pioneer, ES: Early secondary, LS: Late secondary); DS: Dispersal syndrome (Ane: anemochory; Zoo: zoochory; Auto: autochory); Hb: Habit (T: Tree, S: Shrub, P: Palm tree); U: Uncharacterized

Botanical Family / Specie	NI	IV (%)	SC	DS	Hb
Annonaceae					
Annona cacans Warm.	2	0.64	LS	Zoo	T
Guatteria australis A.St.-Hil.	2	0.67	LS	Zoo	T
Xylopia brasiliensis Spreng.	1	0.51	LS	Zoo	T
Arecaceae					
Euterpe edulis Mart.	2	0.64	LS	Zoo	P
Bignoniaceae					
Handroanthus chrysotrichus (Mart. ex DC.) Mattos	5	2.32	ES	Zoo	T
Jacaranda micrantha Cham.	1	0.35	ES	Ane	T
Chrysobalanaceae					
Chrysobalanaceae	1	0.64	U	U	T
Parinari sp.	2	0.87	U	U	T
Clusiaceae					
Garcinia gardneriana (Planch. & Triana) Zappi	1	0.34	LS	Zoo	T
Combretaceae					
Terminalia glabrescens Mart.	1	0.32	LS	Ane	T
Elaeocarpaceae					
Sloanea guianensis (Aubl.) Benth.	1	0.52	LS	Zoo	T
Erythroxylaceae					
Erythroxylum pelleterianum A.St.-Hil.	38	8.47	ES	Zoo	S
Euphorbiaceae					
Alchornea triplinervia (Spreng.) Müll. Arg.	2	0.77	P	Zoo	T
Aparisthmium cordatum (A.Juss.) Baill.	49	18.75	ES	Auto	T
Fabaceae					
Apuleia leiocarpa (Vogel) J.F.Macbr	2	0.65	LS	Ane	T
Bauhinia forficata Link	5	1.93	P	Auto	T
Dalbergia nigra (Vell.) Allemão ex. Benth.	2	0.57	LS	Ane	T
Tachigali rugosa (Mart. ex Benth.) Zarucchi & Pipoly	6	2.52	LS	Ane	T
Hypericaceae					
Vismia guianensis (Aubl.) Choisy	5	0.93	P	Zoo	T
Indeterminate					
Indeterminate 1	1	0.40	U	U	U
Lauraceae					
Nectandra megapotamica (Spreng.) Mez	12	4.98	LS	Zoo	T
Nectandra oppositifolia Nees	25	6.43	LS	Zoo	T
Persea willdenovii Kosterm.	2	0.57	LS	Zoo	T
Melastomataceae					
Miconia budlejoides Triana	1	0.55	P	Zoo	T
Miconia cinnamomifolia (DC.) Naudin	2	0.65	P	Zoo	T
Miconia latecrenata (DC.) Naudin	1	0.31	P	Zoo	T
Miconia pusilliflora (DC.) Naudin	3	0.77	ES	Zoo	T
Meliaceae					
Cabralea canjerana (Vell.) Mart.	1	0.50	ES	Zoo	T
Cedrela fissilis Vell.	1	0.36	LS	Ane	T
Guarea macrophylla Vahl	5	1.76	LS	Zoo	T
Trichilia elegans A.Juss.	6	1.67	LS	Zoo	T
Myristicaceae					
Virola bicuhyba (Schott ex Spreng.) Warb.	4	1.78	LS	Zoo	T
Virola gardneri (A.DC.) Warb.	9	2.91	LS	Zoo	T
Myrtaceae					

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Campomanesia guaviroba (DC.) Kiaersk.	1	0.47	LS	Zoo	T
Eugenia sp.	3	0.82	U	Zoo	T
Myrcia anceps (Spreng.) O.Berg.	3	1.20	LS	Zoo	T
Myrcia splendens (Sw.) DC.	25	6.37	ES	Zoo	T
Nyctaginaceae					
Guapira opposita (Vell.) Reitz	2	0.77	ES	Zoo	T
Piperaceae					
Ottonia sp.	3	0.88	U	U	S
Primulaceae					
Myrsine parvula (Mez) Otegui	4	1.74	ES	Zoo	T
Rubiaceae					
Amaioua guianensis Aubl.	8	2.20	LS	Zoo	T
Faramea multiflora A.Rich. ex DC.	1	0.37	LS	Zoo	S
Genipa americana L.	1	0.32	LS	Zoo	T
Ixora gardneriana Benth.	1	0.31	LS	Zoo	T
Palicourea longipedunculata Gardner	1	0.37	LS	Zoo	S
Psychotria carthagenensis Jacq.	27	5.07	LS	Zoo	T
Psychotria rhytidocarpa Müll.Arg.	10	2.56	LS	Zoo	S
Psychotria sp.	2	0.57	LS	Zoo	S
Psychotria vellosiana Benth.	1	0.99	ES	Zoo	T
Rubiaceae 1	1	0.29	U	U	S
Rubiaceae 2	1	0.29	U	U	S
Rudgea sessilis (Vell.) Müll.Arg	6	1.91	LS	Zoo	S
Rutaceae					
Zanthoxylum rhoifolium Lam.	1	0.29	P	Zoo	T
Salicaceae					
Casearia decandra Jacq.	1	0.30	ES	Zoo	T
Casearia gossypiosperma Briq.	1	0.47	ES	Zoo	T
Sapindaceae					
Matayba guianensis Aubl.	3	0.74	LS	Zoo	T
Siparunaceae					
Siparuna guianensis Aubl.	6	4.30	LS	Zoo	T
Solanaceae					
Vassobia breviflora (Sendtn.) Hunz.	1	0.35	P	Zoo	T
Total	315				

The average density of individuals from natural regeneration differed significantly between the two forests analysed ($p < 0.05$), with the highest number of individuals m^{-2} found in the reference ecosystem (2.62 ± 1.10) in relation to the forest under restoration (0.51 ± 0.45). Average species richness also showed a significant difference between the two forests ($p < 0.05$), with 0.32 ± 0.33 species m^{-2} for A1 forest and 1.58 ± 0.57 species m^{-2} in A2 forest. Families with the greatest species richness in A1 forest were Solanaceae (3), Asteraceae (2) and Fabaceae (2), representing 72.13% of the individuals sampled. Other families were represented by only one species each (Table 1). In A2 forest, the most strongly represented families were the Rubiaceae (12 species), Fabaceae, Melastomataceae, Meliaceae and Myrtaceae (each with four species), making up a total of 40.32% of the individuals sampled (Table 2).

Of all individuals sampled in the A1 forest, the species *Vernonanthura phosphorica*, *Leucaena leucocephala* and *Clidemia hirta* stood out in the phytosociological parameters, together comprising 65.75% of the importance value. In A2 forest, *Aparisthmium cordatum*, *Erythroxylum pelleterianum*, and *Nectandra oppositifolia* represented 33.65% of the importance value.

3.2 Environmental Variables

Soil analysis of A1 forest found moderately low pH, very low phosphorus levels, medium available potassium levels, medium organic matter levels, medium exchangeable calcium and exchangeable magnesium levels, very low exchangeable acidity, medium levels of the sum of bases, potential acidity, effective CEC (t) and CEC pH 7 (T), very low aluminium saturation and medium saturation by bases [27]. Soil analysis of A2 forest found very low pH, very low phosphorus levels, low available potassium levels, high organic matter levels, very low exchangeable calcium and exchangeable magnesium levels, high exchangeable acidity, very low levels of the sum of the bases, very high potential acidity, low effective CEC (t), good CEC pH 7 (T), very high aluminium saturation and very low saturation by bases (Table 3) [27].

Table 3. Soil attribute values in the forest under restoration (A1 forest) and in the reference ecosystem (A2 forest)

Soil attributes	A1 forest	A2 forest
pH in water	5.60	3.90
P (mg dm^{-3})	5.00	1.10
K (mg dm^{-3})	49.00	23.00
P-Rem (mg L^{-1})	17.00	10.20
V (%)	47.10	2.50
m (%)	0.00	85.20
t ($cmol_c$ dm^{-3})	3.20	2.23
T ($cmol_c$ dm^{-3})	6.80	13.03
OM (g Kg^{-1})	40.00	78.88
Ca^{2+} ($cmol_c$ dm^{-3})	2.39	0.19
Mg^{2+} ($cmol_c$ dm^{-3})	0.68	0.08
Al^{3+} ($cmol_c$ dm^{-3})	0.00	1.90
H + Al ($cmol_c$ dm^{-3})	3.60	12.70
SB ($cmol_c$ dm^{-3})	3.20	0.33

Note: P: Phosphorus; K: Potassium; P-Rem: Phosphorus Remnant; V: Bases Saturation Index; m: Aluminium Saturation Index; t: Effective cation exchange capacity; T: Cation exchange capacity at pH 7.0; OM: Organic matter; Ca^{2+}: Exchangeable Calcium; Mg^{2+}: Exchangeable Magnesium; Al^{3+}: Exchangeable Aluminium; H^+ Al: Potential Acidity; SB: Sum of Exchangeable Bases.

The species and scores of axes 1 and 2 used in canonical correspondence analysis are shown in table 4. The eigenvalues of the canonical correspondence analysis for the first two ordering axes were 0.888 (axis 1) and 0.377 (axis 2). In this analysis, the first canonical axis explained 8.8% of the variance and the second axis explained 3.7%, representing together 12.5% of the total variance. The Monte Carlo permutation test showed that the species distribution correlated significantly with the environmental variables ($p < 0.05$).

Table 4. Species, abbreviated names of species and scores of axes 1 and 2 used in the analysis of canonical correspondence

Species	Abbreviation of species names	Scores	
		Axis 1	**Axis 2**
Amaioua guianensis	Ama gui	0.330	-1.191
Bauhinia forficata	Bau for	0.686	-0.631
Cecropia hololeuca	Cec hol	-1.521	0.712
Clidemia hirta	Cli hir	-1.487	0.244
Eugenia sp.	Eug sp.	0.640	-0.447
Euterpe edulis	Eut edu	0.761	-0.455
Guapira opposita	Gua opp	0.671	3.540
Guarea macrophylla	Gua mac	0.724	-0.343
Guatteria australis	Gua aus	0.800	-0.502
Leucaena leucocephala	Leu leu	-1.590	0.382
Miconia cinnamomifolia	Mic cin	0.760	-0.585
Miconia pusilliflora	Mic pus	0.779	0.474
Myrcia anceps	Myr anc	0.673	1.157
Myrcia splendens	Myr spl	0.457	0.882
Myrsine coriaceae	Myr cor	-1.626	-1.230
Myrsine parvula	Myr par	0.736	-0.643
Psychotria carthagenensis	Psy car	0.696	-0.330
Psychotria rhytidocarpa	Psy rhy	0.667	1.382
Psychotria sp.	Psy sp.	0.754	1.216
Rudgea sessilis	Rud ses	0.718	0.507
Solanum mauritianum	Sol mau	-1.627	-1.616
Solanum swartzianum	Sol swa	-1.635	-1.251
Vernonanthura phosphorica	Ver pho	-1.578	0.201
Virola gardneri	Vir gar	0.783	-2.379
Xylopia brasiliensis	Xyl bra	0.703	-0.429

Variables that correlated strongly with the first axis were soil attributes; similarly, the openness of the canopy correlated strongly with the second axis and accumulated litter correlated with the third axis. The weighted correlations showed weak interrelations only between the accumulated litter and soil attributes, and between the accumulated litter and the canopy openness, with eigenvalues lower than 0.5 [29] (Table 5).

Table 5. Canonical Correspondence Analysis (CCA): internal correlations (intraset) in the first three ordering axes and correlation matrix of the weighted environmental variables used in the analysis

Environmental variables	Internal correlations			Weighted correlations		
	Axis 01	Axis 02	Axis 03	Canopy openness	Litterfall accumulated	Soil attributes
Canopy openness	-0.6841*	0.5970*	0.4190	1.000	-	-
Litterfall accumulated	0.4556	-0.4835	0.7474*	-0.287	1.000	-
Soil attributes	-0.9975*	-0.0236	0.0669	0.696*	-0.393	1.000

Note: *Correlations with absolute values > 0.5.

The ordering of canonical correspondence analysis (Figure 2) indicates the formation of a group of species associated with sites with higher concentration of litter and soils with high organic matter and aluminium, such as *Psychotria carthagenensis* and *Guarea macrophylla*, and another group of species associated with more open canopy sites and more fertile soils, such as *Cecropia hololeuca* and *Vernonanthura phosphorica*.

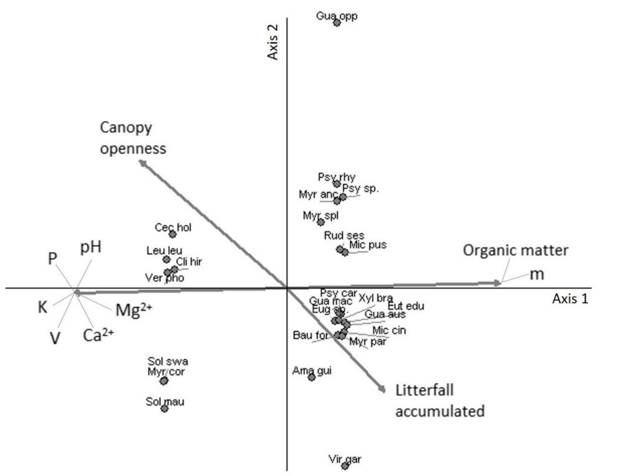

Figure 2. Order of canonical correspondence analysis showing the distribution of species in regard to canopy openness, accumulated litter, and soil attributes. See table 4 for full names of the species

Regarding the distribution of plots, the order of canonical correspondence analysis (Figure 3) also indicates two group formations: one comprising all plots of A1 forest and associated with more open canopy and more fertile soils, and a second comprising all plots of A2 forest and associated with higher concentration of litter and soils with high concentration of organic matter and aluminium.

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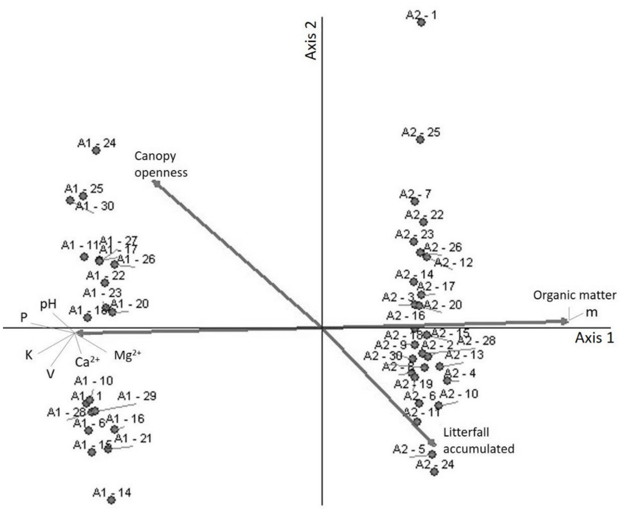

Figure 3. Order of the canonical correspondence analysis showing the distribution of plots with regard to canopy openness, accumulated litter, and soil attributes. A1 - plots of the forest under restoration. A2 - plots of the reference ecosystem

4. Discussion

4.1 Floristic Composition

Natural regeneration is an important process in the restoration of degraded areas. A number of factors determine the efficiency of initial natural regeneration of species, including rainfall and seed bank, area use history, landscape fragmentation, the availability and dispersal of seeds and propagules, presence of dispersers and pollinators, exposure and relief, presence of problematic species (such as invasive alien species) [30], seed predation, and type and intensity of the disturbance on impacted environment [15].

In an area that suffered degradation from bauxite mining and is in a 10-year process of restoration, the restoration model implemented including planting tree species across the total area. This has resulted in the natural regeneration of 80 species belonging to 30 families, with a total of 705 individuals (19,583 individuals ha^{-1}) [31]. In the study cited, the spacing used was tighter (1.0 × 1.0 m), allowing the soil to be covered in a shorter time; this favoured natural regeneration of species over a relatively short period compared to restoration plantings with broader spacing.

In two areas 7 years into the process of restoration in a region belonging to the Atlantic Forest Biome in the south of Brazil, were found 23.333 individuals ha^{-1} belonging to 21 species in one area (where 12 species were planted using 2 × 2 m spacing, within a remnant of old successive tobacco crops), and 11,388 individuals ha^{-1} belonging to 16 species in the other area (where 24 species were planted using 4 × 4 m spacing, in a former village). Both areas are within 600 m of a secondary forest fragment [32].

It is clear from the present study and others in the past that the density of individuals and the number of species in the natural regeneration stratum in restored forests vary widely. This variation can be related to a number of factors, including the stage of restoration, the species used, spacing, condition of surrounding forests, distance from sources of propagules (forest fragments) and others such as those related to the edaphoclimatic conditions.

The botanical families Fabaceae, Rubiaceae, Meliaceae, and Myrtaceae are often found in floristic surveys of natural regeneration in seasonal semi-deciduous forests [31,33,34]. The Asteraceae and Melastomataceae families have an important contribution in natural regeneration in mined soils, as well as in other degraded conditions [35].

The Fabaceae family has a large number of species, many of them with biological nitrogen fixation capacity due to their association with N_2-fixing bacteria, and they also play an important role in the recovery of degraded soils and ecosystem dynamics [36,37] in supply and cycling of nutrients [38].

Rubiaceae is the fourth-richest family in number of species among the Angiosperms, behind only the Orchidaceae, Melastomataceae and Fabaceae families [39]. The great diversity of species of the Rubiaceae family, with representatives in several biomes [39], mostly including small trees or shrubs often present in the understory [40], reveals its importance in ecological studies and the evaluation of the conservation of vegetation in the tropical regions [39].

The specie *Vernonanthura phosphorica*, which belongs to the Asteraceae family, showed comparative importance in the forest restoration process of A1 forest mainly due to its high relative dominance. This specie was also present in the natural regeneration stratum in a secondary forest fragment [41] and in a restored area [42]. It is a pioneer specie, common in early succession areas and adapted to disturbed environments [43].

Leucaena leucocephala is a specie found in the regeneration stratum of the A1 forest which stood out among the most important species, due to its introduction via planting and its early and effective flowering and reproduction. *L. leucocephala* is a pioneer specie and considered aggressive and inhibitory of future succession [44]. Therefore, it is necessary to eradicate the individuals of this invasive alien species and replace them with seedlings of native species.

The presence of a well-preserved forest fragment in the vicinity of the restoration forest, as evaluated in this study,

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probably will facilitate natural enrichment. Thus, a tendency to replace some planted exotic species with native species is expected [45]. In any case, the eradication of *Leucaena leucocephala* is indicated as a preventive measure.

Aparisthmium cordatum is a specie with a great importance value in the reference ecosystem (A2 forest) mainly due to its relative dominance in the area. It is a specie found in forests in an intermediate stage of succession [46], e.g., well-preserved forest remnants.

Erythroxylum pelleterianum was calculated to have the second-largest importance value in A2 forest, mainly due to its high density. Studies of natural regeneration in forest fragments in the Atlantic Forest Biome have recorded the occurrence of this species [47, 48], as well as in forests under restoration [31,33].

It is possible to verify the natural enrichment of the regeneration stratum in A1 forest, with propagules coming from forest fragments of the surroundings, since some species registered in the regeneration are not found among the species used in the forest planting.

4.2 Environmental Variables

The highest levels of K, Ca^{+2}, Mg^{+2}, sum of bases and base saturation index in the restoration forest—indicating a soil with higher fertility—corroborates the findings by [49] in a fragment of Seasonal Semi-Deciduous Forest in the initial stage of succession, as well as the more acidic soil and with higher organic matter levels found in the reference ecosystem of the present study, which was also observed by the [49] in the section of the same forest fragment, which is in an intermediate stage of succession.

The general effect of the chemical characteristics of the soil and canopy structure reflected on the composition of the plant community and on the distinction between the two analysed environments (forest under restoration and reference ecosystem).

The forest under restoration is relatively young (five years) and therefore has a canopy still in formation, with a greater presence of light on the forest floor. In addition, it has a more fertile soil and lower aluminium saturation than the reference ecosystem due to the removal of a soil layer for the extraction of bauxite, mainly composed of aluminium oxide (Al_2O_3), and the base and top soil fertilization applied in the area when implementing the forest restoration.

The reference ecosystem has a more closed canopy, allowing the presence of typical understory species, which require a shaded environment for its development, as do the species of the Rubiaceae family [50] and the *Euterpe edulis* specie [51]. Besides that, forests in medium-advanced stages of succession present higher production of organic matter [52]. And the efficient use of nutrients, favoured by nutrient cycling, makes tree vegetation to be able to remain in environments with low fertility soil, allowing the ecosystem balance [53], as is the case of the species of the reference ecosystem (A2 forest).

Among the species associated with the environment with a more closed canopy and greater presence of aluminium in the soil (reference ecosystem), the species of the genus *Psychotria* are of particular importance for tropical floristic diversity, mainly in the understory composition of many forests [54]. These species may have developed adaptations to edaphic conditions of high aluminium content and higher amount of organic matter [55].

Species associated with the environment with a more open canopy and more fertile soil, such as the *Cecropia hololeuca*, *Vernonanthura phosphorica* and the species of the genus *Solanum*, belong to the group of species that comprise the initial phase of the forest succession (pioneer successional category) and therefore require more light for germination and development [56].

5. Conclusions

The floristic composition and species richness in the regeneration strata of the A1 forest and A2 forest are distinct due to the difference in their environmental variables for each forest. The reference ecosystem favours the presence of species that tolerate environments with greater shade and higher levels of aluminium and organic matter to the soil, while the forest under restoration favours the presence of species adapted to more fertile soils and those that tolerate greater luminosity.

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