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Article

Phytosociology of Ecological Transition Ecosystems in the Anauá National Forest, Roraima State, Brazil

Tiago Monteiro Condé ^{1,*}, Niro Higuchi ¹, Adriano José Nogueira Lima ¹, Moacir Alberto Assis Campos ¹, Joaquim dos Santos ¹, Bruno Oliva Gimenez ¹, Fabiano Emmert ² and Vilany Matilla Colares Carneiro ³

¹ Forest Management Laboratory (LMF), Institute of Amazonian Research (INPA), Av. André Araújo, Manaus 69060-001, AM, Brazil

² Universidade Federal Rural da Amazônia (UFRA), Av. Pres. Tancredo Neves, Belém 66077-901, PA, Brazil

³ Secretaria Estadual de Educação do Estado do Amazonas (SEDUC), Rua Waldomiro Lustoza 250, Japiim II, Manaus 69076-830, AM, Brazil

* Correspondence: tiagonafloresta@gmail.com

Abstract

The northern Brazilian Amazon has ecological transition ecosystems with high diversity and endemism of tree species and few botanical collections. We evaluated the phytosociology between Dense Ombrophilous Forest (Ds) and Forested Campinarana (Ld) within the Anauá National Forest (Flona) in Roraima, Brazil. A total of 14,730 trees with a DBH ≥ 10 cm were inventoried across 30 hectares (ha), distributed among 55 botanical families, 183 genera, 386 species, and 123 undetermined trees. Ten hyperdominant tree families accounted for 69% of the sampled trees and 65% of the stored forest carbon (102.9 ± 5.0 Mg ha⁻¹), like *Areaceae* (2,555), *Fabaceae* (1,738) and *Sapotaceae* (1,311). Ten hyperdominant species accounted for 32% of the sampled individuals and 32% of the stored forest carbon (46.3 ± 3.8 Mg ha⁻¹), like *Euterpe precatoria* (1,151), *Pouteria macrophylla* (561) and *Inga alba* (574). The Anauá National Forest has great potential for sustainable multiple-use forest management through forest concessions; however, tree mortality due to natural causes and anthropogenic actions (deforestation, illegal selective logging, and forest fires) was considered high (7%) for tropical forests in the Amazon. We recommend further studies to broaden the understanding of tree diversity and forest structure present in ecological transition ecosystems in the Brazilian Amazon.

Keywords: Amazon; tree diversity; timber species; forest structure; endemic species

1. Introduction

Phytosociology evaluates the behavior of density, dominance, frequency, phytosanitary status, economic potential, biomass, carbon, and spatial distribution of tree species in the forest structure throughout the natural landscape, using both qualitative and quantitative approaches [1,2]. Metrics obtained through forest inventories can be considered good indicators of environmental quality in natural ecological systems [3] and are extremely important for assessing the degree of impact of climate change caused by natural events and human actions. Thus, changes in floristic composition and forest structure in tropical ecosystems can be detected by assessing the richness and abundance of species that have undergone reduction, increase and extinction because of natural processes, anomalies and anthropogenic actions [4].

Sustainable forest management (SFM) in the Amazon enables the orderly and rational exploitation of timber and non-timber forest products in a selective and legal manner, aiming to combine socioeconomic benefits and environmental sustainability [5]. In contrast, predatory logging is advancing in the Amazon in a selective and illegal manner, generally associated with criminal forest fires, resulting in significant losses of forest carbon, reduced diversity, changes in forest

structure and high tree mortality [6,7]. These changes have contributed to the reduction and disabling of vital interactive ecological processes between flora and fauna, such as pollination, natural regeneration, production of wood, fruits, latex, among others [8]. Mortality in tropical trees can also be associated with different factors, such as growth rate, size (DBH), wood density, loss of photosynthetic efficiency, low resilience and climatic adaptation to natural or anthropogenic disturbances [9].

The conversion of tropical forests into deforested areas in the Amazon [10], mainly to supply the export of valuable timber and agricultural use of international commodities such as meat and soy [11,12], has jeopardized the survival of endemic plant species in ecologically transitional ecosystems. Tropical forests and savannas of the Amazon River Basin and the Guiana Shield, in the Amazon Biome, have the greatest biodiversity on Earth, with an estimated 1,300 species of birds, 427 species of mammals and 50,000 species of seed plants [13–15]. These are natural landscapes marked by the influence of environmental gradients, such as variations in altitude, soil texture and composition, hydromorphic processes, precipitation, and temperature. This mosaic of natural ecosystems is characterized by a highly endemic and diverse floristic composition and forest structure [15–18], with a limited number of botanical collections. Such knowledge is fundamental for the development of conservation strategies, sustainable use of timber and non-timber resources, and mitigation of climate change on Earth.

The central objective of this research was to evaluate the phytosociology of transitional ecosystems in the Anauá National Forest, in southern Roraima, Brazil. The main questions addressed in this study were: (i) Which forest species can be considered hyperdominant and endemic (locally rare)? (ii) What is the potential of timber and non-timber species and their implications for a future scenario of forest management through forest concessions, also aiming at mitigating climate change? (iii) What is the impact of anthropogenic actions on tree species diversity and remaining forest structure?

2. Materials and Methods

2.1. Study Area and Data Collection

The Anauá National Forest (Flona) is a protected area in the far north of the Brazilian Amazon, located in the south of the state of Roraima, Brazil. It is a federal conservation unit administered by the Chico Mendes Institute for Biodiversity (ICMBio/RR) and covers approximately 2,600 km² [19]. Created in 2005, its management plan was approved in 2022 [18,20]. It is part of the white sand ecosystems of the Brazilian Amazon and is considered a region with a high degree of flora endemism and little recorded in botanical collections [17,18,21,22]. It is characterized by seasonal hydrological influences with varying degrees of hydromorphism [22,23]. This area is considered vulnerable to increasing atmospheric carbon emissions caused by human actions associated with deforestation for extensive livestock farming, forest degradation, selective illegal logging, and forest fires [4,7,24].

The forest inventory (FI) of the Anauá National Forest was carried out in 2015, measuring all trees with DBH (diameter at breast height) ≥ 10 cm within 120 rectangular plots of 2500 m² (0.25 ha each), randomly distributed, totaling 30 hectares. Ecological transition ecosystems between Dense Ombrophilous Forest (Ds) and Forested Campinarana (Ld), as defined by the Brazilian Institute of Geography and Statistics (IBGE), were discussed [25].

2.2. Botanical Identification and Taxonomy

The collection and botanical identification of forest species measured in the field during the FI was carried out respecting the Normative Instruction of the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) No. 154/2007, which establishes the rules for conducting scientific research activities in areas of federal conservation units in Brazil. The team consisted of parobotanists, botanists, and forestry engineers from the Forest Management Laboratory (LMF) and the INPA Herbarium in Manaus. One specimen of each taxon was collected (triplicate). The taxonomy of the biological material was carried out at the INPA Herbarium, consisting of the steps of checking,

validating the botanical nomenclature, cataloging and depositing fertile samples, which have reproductive structures. The samples were subjected to drying in an oven (60 °C) for 48 hours and freezing at 0 °C for 48 hours, as described in the INCT Herbaria Procedures Manual [26]. The botanical nomenclature was also checked in virtual herbaria [27–29]. The species were classified by the system proposed by the *Angiosperm Phylogeny Group* [30,31].

2.3. Phytosociological and Data Analyses

The estimation of tree species diversity in the Anauá National Forest was carried out using the Shannon-Wiener index (H), on a natural logarithmic basis [32] and Fisher's alpha (α) [33]. The species abundance ranking was calculated for both forest types (Ds and Ld) using the R software [34].

The assessment of forest structure was carried out using qualitative and quantitative approaches, calculated in Microsoft 365 software (Excel), as follows: a) horizontal structure (density, dominance, frequency, coverage value and ecological importance by species and family) [35]; b) Vertical structure divided into three total height strata (TH): lower stratum - trees with $TH < (x - 1\sigma)$; middle stratum - trees with $(x - 1\sigma) \leq TH < (x + 1\sigma)$ and upper stratum - trees with $TH \geq (x + 1\sigma)$, where x is the mean and σ is the standard deviation of the total heights [1,2]; c) parametric structure (mean, standard deviation and confidence interval - 95% CI), see Supplementary Material - List S1) of diameter (DBH), basal area (BA), total height (TH), commercial timber volume (V), dry biomass (aboveground = AGB; belowground = BGB; total biomass = B) and forest carbon (aboveground = AGC; belowground = BGC; total carbon = C) [2]; d) Internal or phytosanitary structure: fallen live tree (C), live tree damaged by natural causes (D), dead tree fallen due to natural causes (MC), tree killed by illegal selective logging (ME), standing dead tree due to natural causes (MP), tree killed by forest fire (MQ), normal live tree (N), live tree partially burned by forest fire (Q), live tree without crown (SC) and leaning live tree (T) [1,2,4,7].

2.4. Estimates of Total Height, Commercial Volume, Biomass, and Forest Carbon

The development of allometric models for estimating total height (TH) and commercial volume (V) was carried out using rigorous cubing of 171 trees with $DBH \geq 10$ cm of wood that had fallen naturally in the forest, recently illegally logged, and partially burned within and around the Anauá National Forest; see details in [7]. Authorization for scientific activities was obtained from ICMBio No. 45470-2, renewed annually (2014 to 2017) through the submission of reports to the Biodiversity Authorization and Information System - SISBio [36]. In the rigorous timber volume measurement stage, only trees in good phytosanitary condition were selected in terms of trunk and crown quality, regarding timber yield (50, 75 and 100%).

The estimation of biomass stock stored by trees with $DBH \geq 10$ cm in the Anauá National Forest was carried out at three levels using allometric models developed for Dense Ombrophilous Forest (Ds) [37] and Forested Campinarana (Ld) [38,39]. The estimation of forest carbon stock (C) stored by trees was carried out in three stages. Initially, fresh biomass was estimated from the allometric models, using a correction factor (1.098023) for the average dominant height ($H_{dom.} = 33.2$ meters) of 20% of the trees with the largest diameters in the Anauá National Forest in relation to the dominant height ($H_{dom.} = 30.2$ meters) of ZF-2 in Manaus-AM [7]. In the second stage, dry biomass was estimated using a correction factor (0.582) based on the water content of the trees, corresponding to the average of the factors developed for Ds [37] and Ld [39]. In the third stage, forest carbon was estimated based on the specific carbon content of the wood, applying a factor (0.480) corresponding to the average of the factors developed for Ds and Ld mentioned above. The total area of each forest physiognomy (stratum) referring to Ds and Ld was estimated by means of supervised pixel-by-pixel classification using the Maximum Likelihood algorithm on the R(5), G(4), B(3) composition of digital images from the OLI remote sensor of the Landsat-8 platform, in ArcGIS 10.3 software, by detailed method [7].

2.5. Estimation of Tree Mortality from Natural and Anthropogenic Causes

The estimation of tree mortality due to natural and anthropogenic causes was carried out from visual observations in the field during the FI of the Anauá National Forest and, subsequently, by analyzing the FI database. The difference between dead trees that died from natural processes (natural falls, mortality due to drought, pathogens, among others) and dead trees affected by human processes (deforestation, illegal logging and affected by forest fires), excluding live trees, was evaluated by a detailed method [7]. In this study, we assume that the reduction of forest carbon stocks resulting from natural processes alters the gas exchange of the forest ecosystem in the medium to long term. Dead trees that have fallen naturally will retain their stored carbon for a long time, without significant losses to the forest. Trees that have fallen naturally are generally not removed from the forest by loggers because they have low commercial value due to their advanced state of decomposition. In contrast, trees affected by illegal selective logging result in a more pronounced loss of forest carbon stock in the short term, as they are immediately extracted and processed in local sawmills. Forest fires alter the gas exchange of the forest ecosystem in the short term, reducing the forest carbon stock to varying degrees, depending on the incidence and severity of the fires [7,40–42].

3. Results

3.1. Forest Inventory, Taxonomy and Forest Structure

The forest inventory (FI) of the Anauá National Forest demonstrated the existence of a highly endemic and diverse flora in southern Roraima, Brazil. Thirty hectares were inventoried in ecosystems of ecological transition between Dense Ombrophilous Forest (Ds) and Forested Campinarana (Ld), with 14,730 trees with DBH \geq 10 cm measured, distributed among 55 botanical families, 182 genera, 385 species or morphospecies, and 123 trees of undetermined species (Table 1). The complete botanical list can be viewed in Supplementary Material (Table S2). The species that are endemic or locally rare, that is, with less than 1 individual per hectare, totaled 305 (79% of the total sampled).

Table 1. Floristic composition, taxonomy and forest structure of the Anauá National Forest, in southern Roraima, Brazil.

Scientific Name	Trees:	D	DBH	TH	BA	V	Biomass			Carbon		
							AGB	BGB	B	AGC	BGC	C
Anacardiaceae												
<i>Anacardium giganteum</i> W. Hancock ex Engl.	16	0.53	32.0 ± 24.3	19.0 ± 6.7	0.066	0.612	0.8699	0.1790	0.8914	0.4176	0.0859	0.4279
<i>Anacardium parvifolium</i> Ducke	1	0.03	27.5 - -	19.5 - -	0.002	0.015	0.0277	0.0037	0.0292	0.0133	0.0018	0.0140
<i>Anacardium</i> sp.	1	0.03	40.3 - -	23.2 - -	0.004	0.036	0.0575	0.0094	0.0597	0.0276	0.0045	0.0286
<i>Astronium lecointei</i> Ducke	2	0.07	16.3 ± 5.3	15.3 ± 2.3	0.001	0.010	0.0212	0.0022	0.0227	0.0102	0.0010	0.0109
<i>Spondias</i> sp.	57	1.90	40.2 ± 13.2	19.7 ± 2.9	0.266	2.333	3.5666	0.6326	3.6839	1.7120	0.3036	1.7683
<i>Tapirira guianensis</i> Aubl.	18	0.60	28.1 ± 13.4	17.1 ± 2.8	0.045	0.379	0.6175	0.0976	0.6434	0.2964	0.0468	0.3088
Anisophylleaceae												
<i>Anisophyllea guianensis</i> Sandwith	4	0.13	15.3 ± 3.5	14.9 ± 1.6	0.003	0.018	0.0373	0.0037	0.0401	0.0179	0.0018	0.0192
<i>Anisophyllea manausensis</i> Pires & W.A.Rodrigues	1	0.03	18.9 - -	15.0 - -	0.001	0.007	0.0135	0.0014	0.0144	0.0065	0.0007	0.0069
Annonaceae												
<i>Anaxagorea brevipes</i> Benth.	218	7.27	18.2 ± 9.2	15.2 ± 2.8	0.237	1.846	3.3266	0.4430	3.5138	1.5968	0.2126	1.6866
<i>Annona ambotay</i> Aubl.	2	0.07	13.3 ± 2.5	14.0 ± 1.2	0.001	0.006	0.0139	0.0012	0.0150	0.0067	0.0006	0.0072
<i>Annona neoinsignis</i> H. Rainer	2	0.07	17.6 ± 7.7	15.6 ± 3.4	0.002	0.013	0.0254	0.0028	0.0271	0.0122	0.0014	0.0130
<i>Annona</i> sp. 1	19	0.63	16.3 ± 5.8	15.1 ± 2.4	0.015	0.107	0.2130	0.0233	0.2274	0.1022	0.0112	0.1092
<i>Annona</i> sp. 2	1	0.03	10.3 - -	12.5 - -	0.000	0.002	0.0043	0.0003	0.0047	0.0020	0.0002	0.0022
<i>Bocageopsis multiflora</i> (Mart.) R.E.Fr.	202	6.73	17.6 ± 4.5	15.6 ± 1.8	0.174	1.258	2.5017	0.2723	2.6715	1.2008	0.1307	1.2823
<i>Duguetia chrysea</i> Maas	363	12.10	15.7 ± 4.5	14.4 ± 1.5	0.252	1.796	3.6661	0.3806	3.9285	1.7598	0.1827	1.8857
<i>Duguetia trunciflora</i> Maas & A.H.Gentry	3	0.10	15.4 ± 1.6	14.7 ± 0.9	0.002	0.013	0.0276	0.0027	0.0298	0.0133	0.0013	0.0143
<i>Guatteria scytophylla</i> Diels	55	1.83	19.9 ± 9.1	15.3 ± 2.4	0.069	0.537	0.9675	0.1277	1.0212	0.4644	0.0613	0.4902
<i>Guatteria</i> sp.	3	0.10	18.4 ± 6.0	15.5 ± 2.7	0.003	0.021	0.0408	0.0046	0.0435	0.0196	0.0022	0.0209

<i>Onychopetalum amazonicum</i> R.E. Fr.	1	0.03	17.3	-	-	15.8	-	-	0.001	0.006	0.0114	0.0012	0.0122	0.0055	0.0006	0.0059
<i>Xylopia amazonica</i> R.E. Fr.	105	3.50	18.7 ± 5.2	15.9 ± 2.0	0.103	0.759	1.4749	0.1677	1.5705	0.7080	0.0805	0.7538				
<i>Xylopia benthamii</i> R.E.Fr.	8	0.27	11.3 ± 1.2	13.0 ± 0.6	0.003	0.018	0.0409	0.0033	0.0445	0.0196	0.0016	0.0214				
<i>Xylopia polyantha</i> R.E.Fr.	17	0.57	17.2 ± 5.3	15.0 ± 1.7	0.014	0.104	0.2055	0.0225	0.2194	0.0987	0.0108	0.1053				
<i>Xylopia</i> sp.	7	0.23	17.4 ± 2.9	14.6 ± 0.7	0.006	0.041	0.0827	0.0086	0.0885	0.0397	0.0041	0.0425				
Apocynaceae																
<i>Ambelania duckei</i> Markgr.	14	0.47	14.3 ± 5.0	13.7 ± 1.3	0.008	0.059	0.1218	0.0124	0.1307	0.0584	0.0059	0.0627				
<i>Aspidosperma album</i> (Vahl) Benoist ex Pichon	4	0.13	14.9 ± 3.1	14.6 ± 1.5	0.002	0.017	0.0351	0.0034	0.0378	0.0168	0.0016	0.0181				
*Other species ...	...	...	...	...	...	...	...	...	...	...	...	...
Undetermined	123	4.10	24.3 ± 11.7	17.4 ± 3.6	0.234	1.911	3.2181	0.4817	3.3680	1.5447	0.2312	1.6166				
Dead trees	1,033	34.43	21.5 ± 13.4	16.3 ± 3.5	1.742	14.623	23.8278	3.8586	24.8688	11.4373	1.8521	11.9370				
Total (Ds and Ld)	14,730	491	-	-	-	-	-	22.7	187.4	313.2	48.2	327.8	150.3	23.1	157.3	

* Where: Trees_i = total number of individuals per species in the 30 hectares of the forest inventory (FI); D = density of individuals per species per hectare, Trees ha⁻¹; DBH = mean and standard deviation of diameter at breast height, in cm; TH = mean and standard deviation of total height, in meters; BA = basal area per species per hectare, in m² ha⁻¹; V = commercial timber volume per species per hectare, in m³ ha⁻¹; AGB = aboveground dry biomass per species, in Mg ha⁻¹; BGB = belowground dry biomass per species, in Mg ha⁻¹; TB = total dry biomass per species, in Mg ha⁻¹; Carbon: AGC = aboveground carbon per species, in Mg ha⁻¹; BGC = belowground carbon per species, in Mg ha⁻¹; C = total carbon per species, in Mg ha⁻¹. *Other species ...= the complete list can be viewed in Supplementary Material (Table S2).

The 10 tree families with the highest family importance values (FIV_i%) considered hyperdominant in the Anauá National Forest were Fabaceae (1,738), Arecaceae (2,555), Sapotaceae (1,311), Lecythidaceae (906), Annonaceae (1,006), Vochysiaceae (372), Moraceae (453), Chrysobalanaceae (611), Burseraceae (649), and Lauraceae (515), representing 69% of the total individuals sampled and 65% of the stored forest carbon (102,9 ± 5,0 Mg ha⁻¹) (Table 2).

Table 2. Hyperdominant tree families of the Anauá National Forest, in southern Roraima, Brazil.

Ranking	Botanical Family	Horizontal Structure										Carbon		
		Trees _i	BA _i	AD _i	RD _i	ADo _i	RDo _i	ADIV _i	RDIV _i	VC _i %	FIV _i %	AGC	BGC	C
1 ^o	Fabaceae	1,738	104.8	57.9	12.7	3.5	16.6	0.3	5.0	14.7	11.4	22.8	3.8	23.7
2 ^o	Arecaceae	2,555	57.7	85.2	18.7	1.9	9.2	0.3	5.0	13.9	10.9	13.3	1.4	14.3
3 ^o	Sapotaceae	1,311	84.7	43.7	9.6	2.8	13.4	0.3	4.8	11.5	9.3	18.4	3.1	19.1
4 ^o	Lecythidaceae	906	38.1	30.2	6.6	1.3	6.0	0.3	4.8	6.3	5.8	8.4	1.3	8.8
5 ^o	Annonaceae	1,006	26.4	33.5	7.3	0.9	4.2	0.3	4.7	5.8	5.4	6.0	0.7	6.4
6 ^o	Vochysiaceae	372	43.3	12.4	2.7	1.4	6.9	0.3	4.2	4.8	4.6	9.2	1.7	9.5
7 ^o	Moraceae	453	29.7	15.1	3.3	1.0	4.7	0.3	4.6	4.0	4.2	6.5	1.1	6.7
8 ^o	Chrysobalanaceae	611	22.9	20.4	4.5	0.8	3.6	0.3	4.2	4.1	4.1	5.1	0.7	5.4
9 ^o	Burseraceae	649	17.0	21.6	4.7	0.6	2.7	0.3	4.8	3.7	4.1	3.9	0.5	4.1
10 ^o	Lauraceae	515	20.4	17.2	3.8	0.7	3.2	0.3	4.1	3.5	3.7	4.6	0.6	4.8
Subtotal		10,116	445	337	74	15	71	3	46	72	64	98.2	14.9	102.9
Other species*		4,614	237	119	26	6	29	3	54	28	36	52.1	8.2	54.4
Total (Ds and Ld)*		14,730	683	457	100	21	100	6	100	100	100	150.3	23.1	157.3

*Including the count of dead trees. Where: Trees_i = total number of individuals per botanical family in the 30 hectares of the FI; BA_i = basal area per botanical family (m²); DA_i = absolute density per botanical family; RD_i = relative density per botanical family; AD_i = absolute dominance per species; RDo_i = relative dominance per species; ADIV_i = absolute species diversity per botanical family; RDIV_i = relative species diversity per botanical family; CV_i% = coverage value per botanical family (%); ecological importance value per botanical family

(FIV_i%); AGB = aboveground dry biomass per botanical family, in Mg ha⁻¹; BGB = belowground dry biomass per botanical family, in Mg ha⁻¹; B = total dry biomass per botanical family, in Mg ha⁻¹; Carbon: AGC = aboveground carbon per botanical family, in Mg ha⁻¹; BGC = belowground carbon by botanical family, in Mg ha⁻¹; C = total carbon by botanical family, in Mg ha⁻¹.

The 10 forest species with the highest importance values (IV_i%) considered hyperdominant in the Anauá National Forest were *Euterpe precatoria* (1,151), *Pouteria macrophylla* (561), *Inga alba* (574), *Brosimum acutifolium* (358), *Protium rubrum* (504), *Sapium glandulosum* (267), *Attalea maripa* (409), *Astrocaryum murumuru* (536), *Manilkara huberi* (145) e *Qualea paraensis* (194), representing 32% of the total individuals sampled and 32% of the stored forest carbon (46.3 ± 3.8 Mg ha⁻¹) (Table 3).

Table 3. Hyperdominant tree species of the Anauá National Forest, in southern Roraima, Brazil.

Ranking	Species	Horizontal Structure									Carbon			
		Trees _i	BA _i	AD _i	RD _i	ADo _i	RDo _i	AF _i	RF _i	CV _i %	IV _i %	AGC	BGC	C
1 ^o	<i>Euterpe precatoria</i>	1,151	15.8	38.4	8.4	0.5	2.5	81.7	2.1	5.5	4.3	3.7	0.3	4.0
2 ^o	<i>Pouteria macrophylla</i>	561	23.9	18.7	4.1	0.8	3.8	75.0	1.9	3.9	3.3	5.3	0.7	5.6
3 ^o	<i>Inga alba</i>	574	19.4	19.1	4.2	0.6	3.1	85.0	2.1	3.6	3.1	4.4	0.5	4.7
4 ^o	<i>Brosimum acutifolium</i>	358	21.0	11.9	2.6	0.7	3.3	84.2	2.1	3.0	2.7	4.6	0.7	4.8
5 ^o	<i>Protium rubrum</i>	504	10.2	16.8	3.7	0.3	1.6	84.2	2.1	2.6	2.5	2.4	0.2	2.5
6 ^o	<i>Sapium glandulosum</i>	267	26.1	8.9	1.9	0.9	4.1	44.2	1.1	3.0	2.4	5.6	1.0	5.9
7 ^o	<i>Attalea maripa</i>	409	19.7	13.6	3.0	0.7	3.1	43.3	1.1	3.1	2.4	4.4	0.6	4.7
8 ^o	<i>Astrocaryum murumuru</i>	536	12.9	17.9	3.9	0.4	2.0	43.3	1.1	3.0	2.3	3.0	0.3	3.2
9 ^o	<i>Manilkara huberi</i>	145	27.3	4.8	1.1	0.9	4.3	36.7	0.9	2.7	2.1	5.7	1.2	5.8
10 ^o	<i>Qualea paraensis</i>	194	23.2	6.5	1.4	0.8	3.7	45.0	1.1	2.5	2.1	4.9	0.9	5.1
Subtotal		4,699	200	157	34	7	32	623	16	33	27	44.1	6.6	46.3
Other species*		10,031	483	300	66	14	68	3,358	84	67	73	95.4	14.8	99.8
Total (Ds and Ld)		14,730	683	457	100	21	100	3,980	100	100	100	139.5	21.3	146.0

*Including the count of dead trees. Where: Trees_i = total number of individuals per species in the 30 hectares of the FI; BA_i = basal area per species (m²); AD_i = absolute density per species; RD_i = relative density per species; ADo_i = absolute dominance per species; RDo_i = relative dominance per species; AF_i = absolute frequency per species; RF_i = relative frequency per species; CV_i% = coverage value per species (%); ecological importance value per species (IV_i%); AGB = aboveground dry biomass per species, in Mg ha⁻¹; BGB = belowground dry biomass per species, in Mg ha⁻¹; B = total dry biomass per species, in Mg ha⁻¹; Carbon: AGC = aboveground carbon per species, in Mg ha⁻¹; BGC = belowground carbon per species, in Mg ha⁻¹; C = total carbon per species, in Mg ha⁻¹.

The abundance ranking by species highlighted the hyperdominance of palm trees such as *E. precatoria*, *A. maripa*, *O. bacaba*, among others, for both forest types (Ds and Ld). This fact demonstrates the great potential for exploitation of non-timber forest products (NTFPs) originating from the Areaceae family (Figure 1). Dead trees were represented in this study as a single species, aiming to assess their representativeness, showing high abundance (7%; 1,033; 34 trees ha⁻¹) for tropical forests of the Brazilian Amazon, denoting signs of environmental disturbance.

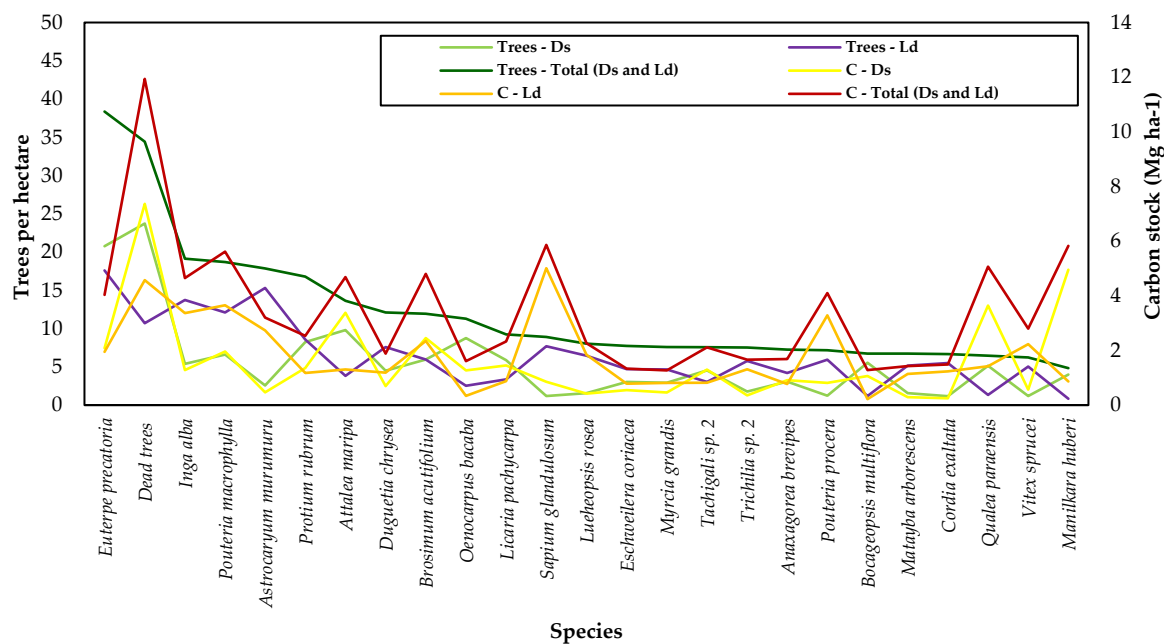


Figure 1. Ranking of tree species abundance and stored forest carbon in the Anauá National Forest, southern Roraima, Brazil.

In forest inventory (FI) of the Anauá National Forest (Flona), higher diversity values were observed for Dense Ombrophilous Forest - Ds ($H' = 4.43$; $\alpha = 75.27$) compared to Forested Campinarana - Ld ($H' = 4.26$; $\alpha = 57.23$), values considered intermediate in relation to studies carried out in the Brazilian Amazon (Table 4).

Table 4. Comparisons between diversity metrics for Dense Ombrophilous Forest (Ds), Forested Campinarana (Ld) and Campinarana/Ombrophilous Forest Contact (LO) environments in the Brazilian Legal Amazon.

Authors	Brazilian Legal Amazon	Ds	LO	Ld	H'	α
Condé et al., 2025	Rorainópolis-RR	X			4,43	75,27
(This study)				X	4,26	57,23
Condé e Tonini (2013)	Caracará-RR	X			3,27	-
Alves e Miranda (2008)	Almeirim-PA	X			4,25	-
Oliveira <i>et al.</i> (2008)	Manaus-AM	X			5,10	-
Miranda (2000)	Pimenta Bueno-RO	X			3,88	-
Oliveira e Mori (1999)	Projeto Dinâmica Biológica de Fragmentos Florestais (PDBFF) próximo à Manaus-AM		X		-	205,08
Amaral (1996)	Região do Rio Urucu-AM	X			-	140,51
Tello (1995)	Manaus-AM		X		-	53,01

Where: Ds = Dense Ombrophilous Forest; LOt = Campinarana/Ombrophilous Forest Contact; Ld = Forested Campinarana; H' = Shannon index; α = Fisher's alpha.

The vertical structure of the Anauá National Forest was represented by three well-defined vertical strata, with higher tree frequencies observed in the middle and upper strata in both forest types (Ds and Ld) (Figure 2).

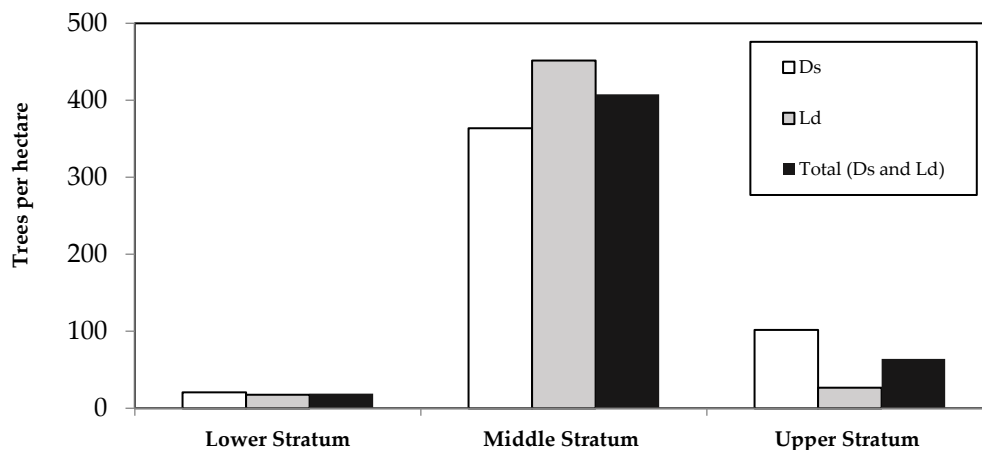


Figure 2. Frequency of trees per hectare by vertical stratum in the phytophysiognomies of Dense Ombrophilous Forest (Ds) and Forested Campinarana (Ld) and Total (Ds and Ld) of the Anauá National Flona. Where: EI = lower stratum ($TH < 12.6$ m); EM = middle stratum ($12.6 \leq TH < 19.1$ m); ES = upper stratum ($TH \geq 19.1$ m); $\bar{x} = 15.9$ m; $\sigma = 3.3$ m.

3.2. Timber and Non-Timber Potential in a Future Scenario of MFS Through Forest Concessions

The assessment of the internal or phytosanitary structure of the Anauá National Forest, carried out on the 30 hectares of the FI (14,730 trees), found that most trees were considered normal without any apparent damage (N: 90%; 13,198 trees; 440 trees ha^{-1}). This demonstrates that the forest is in good condition, especially in the Western Region, which is further away from human occupation. Mortality associated with natural causes, such as trees that died due to natural causes (MC: 1.2%; 180 trees; 6 trees ha^{-1}) and standing dead trees due to natural causes (MP: 3.1%; 458 trees; 15 trees ha^{-1}), totaled 4.3% of the total number of trees in the FI. Mortality associated with anthropogenic causes, such as deforestation, forest degradation, and forest fires, totaled 3.9%, comprising trees killed by selective illegal logging (ME: 0.2%, 26 trees; 0.9 trees ha^{-1}), and trees killed by forest fires (MQ: 3.7%, 549 trees; 18.3 trees ha^{-1}). Live trees that had suffered some type of stress, mainly due to forest degradation from selective illegal logging, totaled 0.04%, consisting of live trees without crowns (SC: 0.03%, 5 trees; 0.2 trees ha^{-1}) and live trees partially burned by forest fire (Q: 0.01%, 1 tree; 0.03 trees ha^{-1}). The minority (2.2%) corresponded to fallen trees (C: 0.1%; 12 trees; 0.4 trees ha^{-1}), crooked trees (T: 2%; 292 trees; 9.7 trees ha^{-1}) and trees damaged by natural causes (D: 0.1%; 9 trees; 0.3 trees ha^{-1}) (Figure 3).

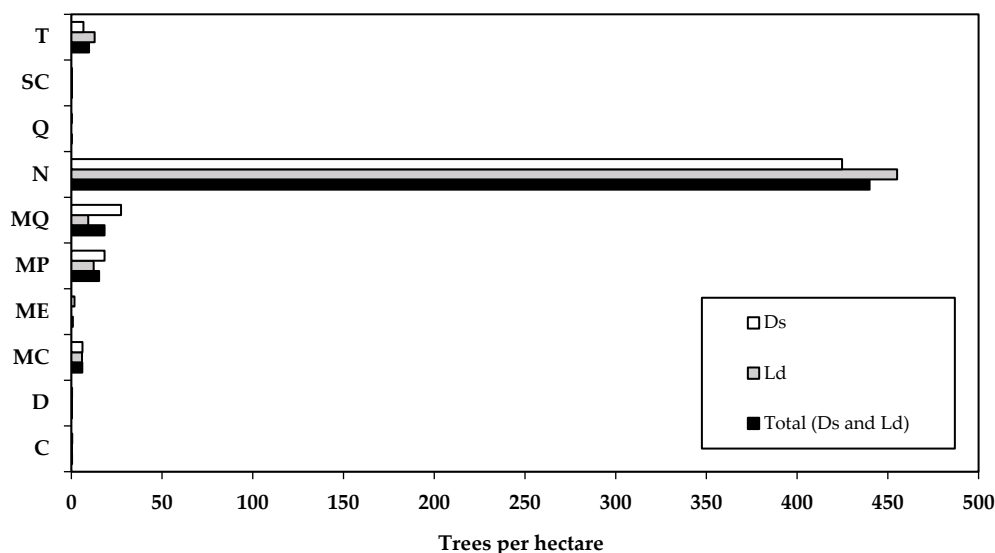


Figure 3. Evaluation of the internal or phytosanitary structure of trees with DBH ≥ 10 cm per hectare in the Anauá National Forest, in southern Roraima, Brazil. Where: C = fallen live tree; D = live tree damaged by natural causes; MC = dead tree fallen due to natural causes; ME = tree killed by illegal selective logging; MP = standing dead tree due to natural causes; MQ = dead tree burned by forest fire; N = normal live tree; Q = live tree partially burned by forest fire; SC = live tree without crown; T = crooked live tree.

The Anauá National Forest presented a frequency of trees by diameter that was quite similar in Dense Ombrophilous Forest (Ds) and Forested Campinarana (Ld) ecosystems (Figure 4). Initially, this fact may raise doubts about the accuracy of supervised digital image classification (*Maximum Likelihood*) by forest types, considering the concept of the predominance of thicker trees in Ds environments compared to Ld. However, it should be noted that of the 30 hectares sampled in the FI of the Anauá National Forest, half were classified as Ds (15) and the other half as Ld (15 ha), due to the fact that the total area or the majority of the plot area (area 0.25 ha) overlapped the respective forest physiognomy. Regions of ecological transition or contact between Campinarana and Dense Ombrophilous Forest (LOt) totaled 67 of the 120 sampled plots (56%), thus the decision criterion was defined based on the largest area occupied in relation to Ds and Ld per plot.

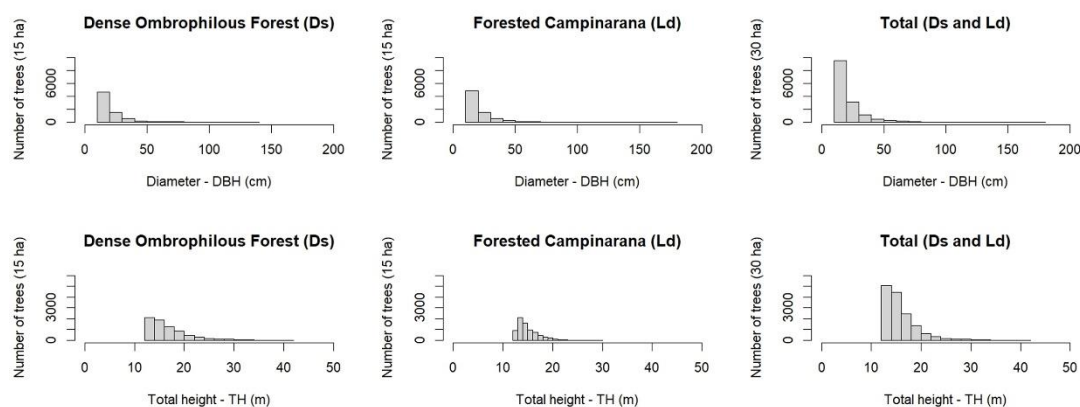


Figure 4. Frequency of trees by diameter, total height and forest typology of the Anauá National Forest, in southern Roraima, Brazil.

The basal area stock per hectare ($\text{m}^2 \text{ha}^{-1}$) in Dense Ombrophilous Forest (Ds) and Forested Campinarana (Ld) was considered similar (ANOVA, $p_{value} = 0,2530$) (Table 5). Regarding the commercial volume of timber stock ($\text{m}^3 \text{ha}^{-1}$), there is strong evidence of a difference between forest physiognomies (ANOVA, $p_{value} < 0,0001$), on average the timber volume production per hectare is higher in Ds compared to Ld. However, when we consider the areas mapped by forest physiognomy, that is, the size per stratum within the Anauá National Forest, the basal area and commercial volume stocks in Campinarana Florestada (116,907 ha) were higher compared to the Dense Ombrophilous Forest (71,161 ha).

Table 5. Estimated number of trees, basal area, and commercial timber volume per hectare and per mapped area (stratum) in Dense Ombrophilous Forest (Ds), Forested Campinarana (Ld), and General Forest (Ds and Ld) for the Anauá National Forest, in southern Roraima, Brazil.

Forest physiognomies	Stratum (ha)	Trees		BA		V					
		(ha)		($\text{m}^2 \text{ha}^{-1}$)	(10^6m^2)	($\text{m}^3 \text{ha}^{-1}$)	(10^6m^3)				
Ds	71.161	486	± 21	23,2	± 1,1	1,7	± 0,1	192,9	± 10,9	13,7	± 0,1
Ld	116.907	496	± 23	22,3	± 1,3	2,6	± 0,1	162,6	± 10,4	19,0	± 0,9
Total	188.068	492	± 16	22,6	± 0,8	4,3	± 0,2	174,1	± 7,4	32,7	± 1,4

(Ds and Ld)

Where: Stratified Random Sampling (SRS) = 15 hectares in Ds and 15 hectares in Ld; Mapped area (ha) = spectrally classified by pixel (*Maximum Likelihood*) in the R(5), G(4), B(3) composition of the OLI sensor of the Landsat-8 platform; NOTE = values referring to the mean (\bar{x}) and confidence interval (95% CI).

Aboveground dry biomass (AGB), belowground dry biomass (BGB), and total biomass (B) stocks per hectare were higher in Ds compared to Ld (ANOVA, p -value < 0.0001) (Table 6). Aboveground forest carbon (AGC), belowground forest carbon (BGC), and total carbon (C) stocks per hectare were also higher in Ds compared to Ld (ANOVA, p -value < 0,0001).

Table 6. Estimate of dry biomass and forest carbon stored per hectare, by mapped area (stratum) and by forest typology of the Anauá National Forest, in southern Roraima, Brazil.

Forest physiognomies	Stratum (ha)	Biomass					
		AGB		BGB		B	
		(Mg ha ⁻¹)	(10 ⁶ Mg)	(Mg ha ⁻¹)	(10 ⁶ Mg)	(Mg ha ⁻¹)	(10 ⁶ Mg)
Ds	71.161	322,3 ± 14,2	22,9 ± 0,1	49,8 ± 3,5	3,5 ± 0,1	332,3 ± 14,2	23,6 ± 0,1
Ld	116.907	213,9 ± 21,7	25,0 ± 1,5	26,4 ± 4,0	3,1 ± 0,3	245,1 ± 25,8	28,7 ± 1,8
Total (Ds and Ld)	188.068	254,9 ± 13,3	47,9 ± 2,5	35,3 ± 2,7	6,6 ± 0,5	278,1 ± 15,0	52,3 ± 2,8

Forest physiognomies	Stratum (ha)	Carbon					
		AGC		BGC		C	
		(Mg ha ⁻¹)	(10 ⁶ Mg)	(Mg ha ⁻¹)	(10 ⁶ Mg)	(Mg ha ⁻¹)	(10 ⁶ Mg)
Ds	71.161	156,3 ± 6,9	11,1 ± 0,1	24,2 ± 1,7	1,7 ± 0,1	161,2 ± 6,9	11,5 ± 0,1
Ld	116.907	101,6 ± 10,3	11,9 ± 0,7	12,5 ± 1,9	1,5 ± 0,2	116,4 ± 12,2	13,6 ± 0,8
Total (Ds and Ld)	188.068	122,3 ± 6,3	23,0 ± 1,2	16,9 ± 1,3	3,2 ± 0,2	133,3 ± 7,2	25,1 ± 1,4

Where: Stratified Random Sampling (SRS) = 15 hectares in Ds and 15 hectares in Ld; Mapped area (ha) = spectrally classified by pixel (*Maximum Likelihood*) in the R(5), G(4), B(3) composition of the OLI sensor of the Landsat-8 platform; AGB = aboveground dry biomass; BGB = belowground dry biomass; B = total dry biomass; AGC = aboveground carbon; BGC = belowground carbon; C = total carbon; NOTE = values referring to the mean (\bar{x}) and confidence interval (95% CI).

The spatial distribution map of forest phytophysiological (Ds and Ld) with the average carbon stock and uncertainty (95% CI) per hectare can be seen in Figure 5.

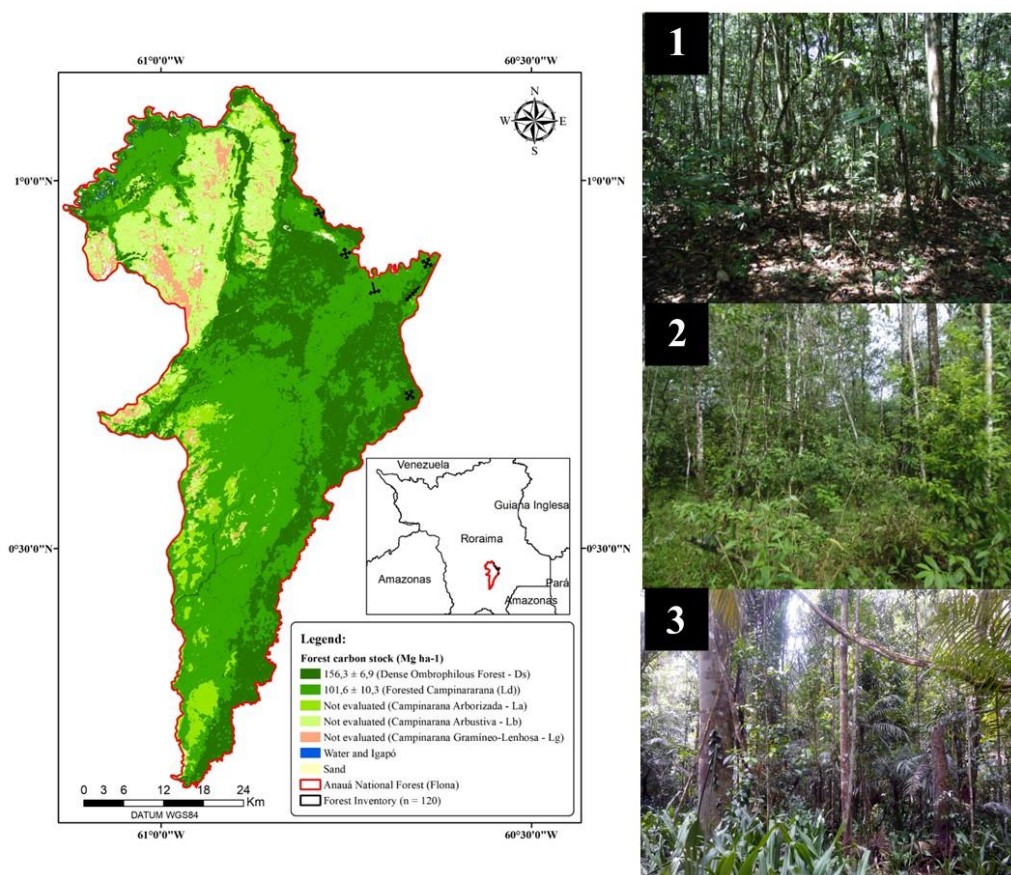


Figure 5. Forest physiognomies and average forest carbon stock per hectare in the Anauá National Forest, southern Roraima, Brazil. Where: Area mapped by supervised pixel-by-pixel classification (*Maximum Likelihood*) in the R(5), G(4), B(3) composition of the OLI remote sensor of the Landsat-8 platform; Photo 1 = Forested Campinararana (Ld); Photo 2 = ecological transition ecosystem (Ecotone) between Ds and Ld (LOt); Photo 3 = Dense Ombrophilous Forest (Ds).

It was estimated that dense ombrophilous forest (Ds) has a higher potential for timber harvesting compared to forested savanna (Ld), considering the parameters of trees per hectare (Trees per hectare: ANOVA, $p_{value} < 0,0001$) and commercial timber volume (V: ANOVA, $p_{value} < 0,003$), specifically for trees with a DBH ≥ 50 cm, which theoretically would be suitable for commercial exploitation (Table 7). However, it should be noted that not all trees with a DBH ≥ 50 cm can be harvested, according to current forestry legislation specific to SFM in the Brazilian Amazon [5,43,44]. The potential for exploitation of non-timber forest products (NTFPs) was estimated, considering only individuals of the Arecaceae family, in Ds of $88,9 \pm 14,9$ palm trees ha^{-1} (21%) and stratum ($6,3 \pm 0,1 \times 10^6$ palm trees) and in Ld of $80,4 \pm 14,7$ palm trees ha^{-1} (19%) and stratum ($9,4 \pm 1,2 \times 10^6$ palm trees).

Table 7. Estimate of the potential for exploitation of timber forest products (TFP) and non-timber forest products (NTFP) per hectare and per mapped area (Strata) for the Anauá National Forest, in southern Roraima, Brazil.

Category 1: Palm trees and juvenile trees with a diameter between $10 \leq DBH < 31.8$ cm					
NTFPs	Forest physiognomies	Juvenile trees		Juvenile commercial volume	
		ha (m ³)	Stratum (10 ⁶ m ³)	ha (m ³)	Stratum (10 ⁶ m ³)
	DS	422.3 ± 20.8	30.1 ± 0.1	77.6 ± 2.8	5.5 ± 0.1
	LD	431.3 ± 22.4	50.4 ± 1.8	74.1 ± 3.9	8.7 ± 0.3

Total (Ds and Ld)		427.9 ± 15.3	80.5 ± 2.9	75.4 ± 2.5	14.2 ± 0.5
Category 2: Pre-harvestable trees with a diameter between $31.8 \leq \text{DBH} < 50.0$ cm					
Forest physiognomies		Pre-exploitable trees		Volume comercial pré-explorável	
		ha (m ³)	Stratum (10 ⁶ m ³)	ha (m ³)	Stratum (10 ⁶ m ³)
NTFPs and TFP	DS	42.5 ± 4.0	3.0 ± 0.1	42.4 ± 4.1	3.0 ± 0.1
	LD	48.5 ± 4.8	5.7 ± 0.4	43.4 ± 4.5	5.1 ± 0.4
	Total (Ds and Ld)	46.2 ± 3.1	8.7 ± 0.6	43.0 ± 3.0	8.1 ± 0.6
Category 3: Exploitable trees with $\text{DBH} \geq 50.0$ cm					
Forest physiognomies		Explorable trees		Exploitable commercial volume	
		ha (m ³)	Stratum (10 ⁶ m ³)	ha (m ³)	Stratum (10 ⁶ m ³)
TFP	DS	21.2 ± 2.4	1.5 ± 0.1	72.9 ± 11	5.2 ± 0.1
	LD	16.2 ± 2.3	1.9 ± 0.2	45.1 ± 9.1	5.3 ± 0.8
	Total (Ds and Ld)	18.1 ± 1.6	3.4 ± 0.3	55.6 ± 7.0	10.5 ± 1.3

Where: Stratified Random Sampling (SRS) = 15 hectares in Ds and 15 hectares in Ld; Mapped area (ha) = spectrally classified by pixel (*Maximum Likelihood*) in the R(5), G(4), B(3) composition of the OLI sensor of the Landsat-8 platform; Strata: 71,161 ha of Dense Ombrophilous Forest (Ds); 116,907 ha of Forested Campinarana (Ld); 188,068 ha of Total (Ds and Ld); NOTE = values referring to mean (x) and confidence interval (95% CI).

3.3. Impact of Anthropogenic Actions on Tree Species Diversity and Remaining Forest Structure

The impact of anthropogenic actions on tree species diversity and forest structure was associated with deforestation, forest degradation, and forest fires, totaling 3.9% of total mortality, comprised of trees killed by illegal selective logging (ME: 0.2%, 26 trees; 0.9 trees ha⁻¹) and trees killed by forest fire (MQ: 3.7%, 549 trees; 18.3 trees ha⁻¹). *In situ* evidence was observed that these practices related to deforestation, forest degradation, and forest fires can considerably reduce the diversity of flora and fauna species, emit large quantities of greenhouse gases (GHG) into the atmosphere, and significantly reduce the stocks of forest volume, biomass, and carbon within and around the Anauá National Forest (Figure 6).

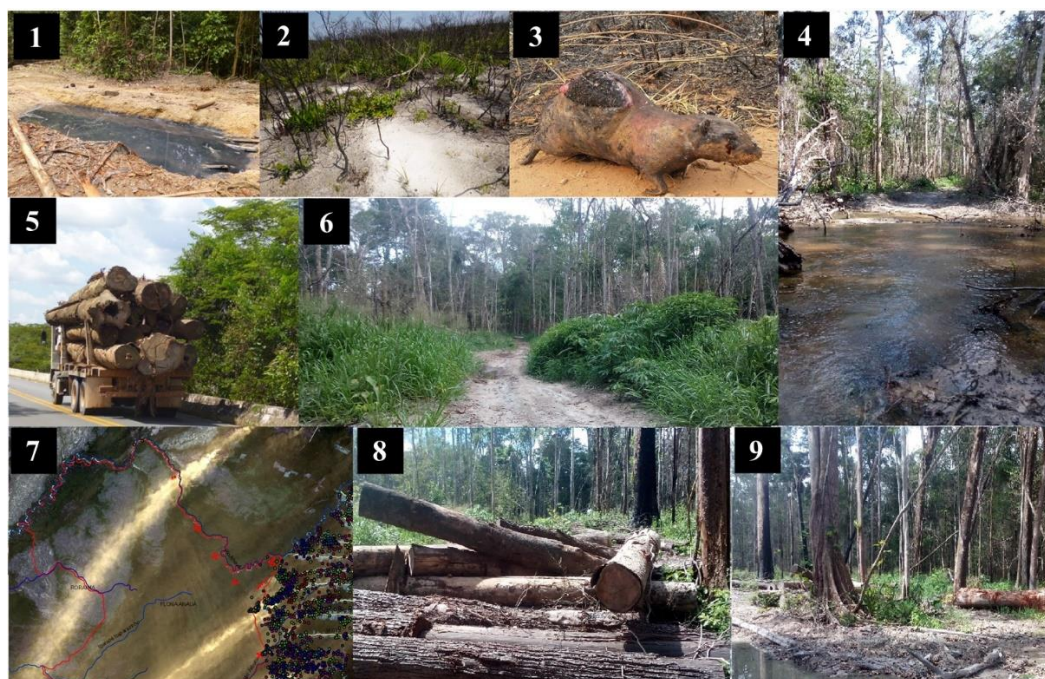


Figure 6. *In situ* evidence of anthropogenic activities related to deforestation, forest degradation, and forest fires within and around the Anauá National Forest, in southern Roraima, Brazil. Where: 1) Pollution of nature by petroleum derivatives used in chainsaws for illegal selective logging at the entrance to the Anauá National Forest; 2) Scars from forest fires in Campinarana Gramíneo-Lenhosa (Lg) environments surrounding the Anauá National Forest; 3) Mortality of wildlife due to forest fires in January 2017; 4) Forest degradation and forced burying of the Jaburu River for the implementation of an illegal timber haulage branch within the Anauá National Forest; 5) Truck carrying illegally extracted timber from within the Anauá National Forest by "middlemen" to a sawmill; 6) Haulage branch built within the National Forest to exploit illegal timber with a high level of forest degradation; 7) Image from the Landsat 8 remote sensing system (OLI) showing smoke at two main points in rural areas of Rorainópolis-RR and Caracarái-RR, associated with more than 500 fire outbreaks monitored by INPE (<http://www.inpe.br/queimadas>) during the period from January to February 2017; 8) Illegal timber storage yard inside the Anauá National Forest; 9) Severe forest degradation associated with selective illegal logging and forest fires within the Anauá National Forest, causing significant soil exposure.

During the period from October 2015 to January 2017, there were major changes in land use and land cover within and around the Anauá National Forest (Flona) associated with deforestation, forest degradation and forest fires (Figure 7).

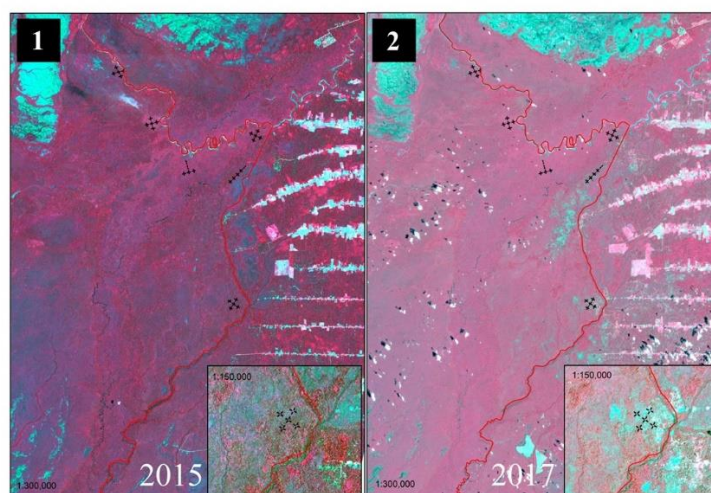


Figure 7. Use of reflectance images in the visible (Red and Green) and near-infrared (NIR) range from the Landsat 8 satellite for the detection of changes in land use and land cover caused by deforestation, forest degradation and forest fires in the period from 2015 to 2017 within and around the Anauá National Forest, in southern Roraima, Brazil. Where: 1) Vegetation in red using the near-infrared (NIR) band; 2) Changes in vegetation due to anthropogenic actions are shown in light blue tones, characterizing deforestation, forest degradation and forest fires; NOTE: more details [7].

4. Discussion

The Brazilian government, to contain or "shield" the advance of predatory exploitation of natural resources in public areas, created Conservation Units (UCs), in accordance with Law No. 9,985/2000 [45]. The National Forest (Flona) aims for the sustainable multiple use of forest resources and scientific research, emphasizing sustainable forest management (SFM). However, currently, most of the National Forests in Brazil are under some type of human pressure (e.g., Tapajós National Forest, Jamari National Forest, among others) and overlap with economically viable areas for logging [46,47]. Created in 2005, the Anauá National Forest only had its Management Plan (MP) approved in 2022 [48], and before that it was extremely vulnerable to human activity through deforestation, forest degradation and criminal forest fires for several years [7].

Our results demonstrated that the Anauá National Forest has great potential for the exploitation of timber forest products (TFP) and non-timber forest products (NTFPs), however, it must be conducted within the context of MFS through forest concessions [5,43,45], mainly due to the endemic biodiversity of the arboreal flora present in the ecological transition ecosystems of white sand in southern Roraima [49]. The commercial volume stock of timber present in large trees (DBH \geq 50 cm) suitable for MFS is around 5.2 ± 0.1 million m^3 of timber in Dense Ombrophilous Forest (Ds) and 5.3 ± 0.8 million m^3 of timber in Forested Campinarana (Ld), taking into account the legal limits for cutting volume per hectare and the rarity criterion of species (Table 7).

The three timber species with the highest commercial volumes and forest carbon stocks per hectare were *Manilkara huberi* ($8.5 \text{ m}^3 \text{ ha}^{-1}$; 5.8 Mg ha^{-1}), *Qualea paraensis* ($6.9 \text{ m}^3 \text{ ha}^{-1}$; 5.1 Mg ha^{-1}), and *Goupia glabra* ($4.3 \text{ m}^3 \text{ ha}^{-1}$; 2.9 Mg ha^{-1}), and are currently among the most exploited timber species in Roraima [1,50]. However, it should be noted that the majority of the timber volume and forest carbon stock is present in endemic or locally rare species, with less than one individual per hectare (79% of the total sampled). The potential for NTFPs is also high, given the high density of palm species, allowing for the extraction of fruits, seeds, leaves, oils, etc., mainly from the hyperdominant species *E. precatória* ($15.8 \text{ palms ha}^{-1}$).

The use and conservation of ecosystem services provided by tropical forests must be linked to the sustainable exploitation of multiple timber and non-timber products in the Amazon, enabling economic profitability and generating benefits for society [51]. Strengthening environmental education through public policies aimed at society is the path to respect for nature, because we can only value and conserve what we know. Sustainable Forest Management (SFM), when implemented rationally, can be considered land use that allows for the exploitation of forest resources combined with their perpetuation for future generations, as it utilizes a series of premises such as reduced-impact logging and chain-of-custody monitoring [4,52–54], physical security and guarantee of social rights at work, respect for current law [55,56], adding value to forest products through forest certification [57], opportunity to trade credits in the global carbon market [58], regulation of ecosystem services and quantification of environmental services in the Amazon [59,60]. Unfortunately, in the state of Roraima, SFM is still considered incipient, being largely surpassed by the conversion of native forests aimed at expanding agriculture [61].

Analysis of the vertical structure of the Anauá National Forest revealed the superiority of trees per hectare occupying the middle stratum ($12.6 \leq \text{TH} < 19.1 \text{ m}$) in Ds (75%) and Ld (93%), similar to several studies carried out in Roraima [1,62] (Figure 2). In comparison with Ds of Caracaraí-RR [1], the Anauá National Forest obtained similar values in relation to the lower stratum ($\text{TH} < 12.4 \text{ m}$; $\text{TH} < 12.6 \text{ m}$) and distinct values for the middle stratum ($12.4 \leq \text{TH} < 26.5 \text{ m}$; $12.6 \leq \text{TH} < 19.1 \text{ m}$) and

upper stratum ($TH \geq 26.5$; $TH \geq 19.1$ m), respectively, demonstrating a predominance of trees with greater total heights in Caracaraí than Rorainópolis, both in the south of Roraima. This fact may be related to the predominance of clayey soils rather than sandy soils in Caracaraí compared to Rorainópolis.

Tropical rainforests represent enormous stocks of biomass and forest carbon, and are considered vital for the Earth's climate balance. It is essential to understand how stored forest carbon is associated with the richness and diversity of tropical flora species, requiring the development of conservation and sustainable use strategies for natural resources in harmony with the preservation of endemic or rare species. In the Anauá National Forest, aboveground dry biomass stocks (AGB), belowground dry biomass stocks (BGB), and total biomass (B) per hectare were higher in Ds compared to Ld (ANOVA, $p_{value} < 0,0001$) (Table 4). Consequently, aboveground, belowground, and total forest carbon stocks per hectare were also higher in Ds compared to Ld (ANOVA, $p_{value} < 0,0001$), corroborating with other studies carried out in the Amazon [39–42]. Just ten hyperdominant tree families accounted for 69% of the total individuals sampled and 65% of the forest carbon ($102,9 \pm 5,0$ Mg ha⁻¹). However, most of the diversity of forest species can be considered endemic or rare locally, resulting in a higher concentration of stored forest carbon (68%) ($110,1 \pm 5,2$ Mg ha⁻¹), indicating a high degree of need for further botanical and taxonomic studies to promote knowledge and appreciation of the intrinsic arboreal biodiversity of the Brazilian Amazon.

Due to the accelerated pace of deforestation, forest degradation, and forest fires driven mainly by agriculture, a large part of the biodiversity of the endemic flora of southern Roraima is being lost without even being scientifically known. The potential of timber and non-timber resources is being extracted legally and illegally, through fraudulent mechanisms [63], failing to generate financial resources for the federal government through forest concessions by SFM [6]. However, monitoring and enforcement activities are considered weak elements in Brazilian forest concessions, and actions are needed to ensure the sustainability of forests considering the increasing illegal logging [64]. In the state of Roraima, selective illegal logging is associated with a complex network of illegal logging and trade, with ramifications in politics and various state and federal agencies, as reported by the Federal Police in operations “Salmo 96” in 2012 [65] “Xilófagos” in 2014 [66]. The low representation of parliamentarians (deputies and senators) committed to the development and strengthening of SFM in the Amazon also contributes to the expansion of public policies focused solely on the growth of agribusiness, under the traditional model of land use in the Amazon, associated with deforestation, forest degradation, and uncontrolled burning for land clearing, facilitating the occurrence and spread of large forest fires, especially in years of severe drought influenced by the El Niño climate phenomenon.

We recommend conducting further botanical and taxonomic studies in ecological transition ecosystems between savanna and forest in the Brazilian Amazon, aiming to expand knowledge of the associated flora and fauna. It is essential to carry out forest inventories encompassing information on flora biodiversity, carbon stock, and ecosystem services, in order to support the development of public policies for strengthening sustainable forest management in the Amazon, under the sustainable use of natural resources in harmony with socioeconomic development in the Northern Region of Brazil.

5. Conclusions

The Anauá National Forest has great potential for implementing sustainable forest management (SFM) for multiple uses, due to its extensive coverage of Dense Ombrophilous Forest (Ds) and Forested Campinarana (Ld), associated with commercially valuable timber species such as *Manilkara huberi*, and high density and dominance of palm trees, such as the hyperdominant *Euterpe precatória*. However, both forest physiognomies have unique ecological characteristics and different potentials for the exploitation of timber and non-timber forest products that should be considered for future multiple-use forest management through forest concessions.

The recently approved Management Plan for the Anauá National Forest is the first step towards mitigating the growing impact of human activities related to deforestation, forest degradation, and forest fires in southern Roraima. However, it is vital to implement inspection, environmental monitoring, and forest concessions in this conservation unit, aiming to contribute to generating revenue for the federal government through the sustainable exploitation of timber and non-timber forest products by SFM. The absence of public power facilitates the perpetuation of activities that degrade the environment, contributing to the reduction of timber, biomass, and forest carbon stocks, causing the mortality of endemic and rare tree species in southern Roraima.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, List S1: Stratified Random Sampling (SRS) was calculated using the following mathematical expressions [2]. Where: N = total number of sample units in the population; M = total number of strata; N_j = total number of sample units in each j -th stratum, $j = 1, 2, \dots, M$; n = number of sample units cast in all strata; n_j = number of sample units cast in each j -th stratum; \bar{Y}_j = estimated mean of the variable Y in each j -th stratum; Y_{ij} = quantity of the variable Y in the i -th sample unit, of the j -th stratum; \bar{Y} = stratified mean or weighted mean; P_j = proportion of the total area of each stratum in relation to the total area; \hat{Y}_j = estimated total value of Y for the population; \hat{Y}_j = estimated total value of Y for each j -th stratum; S_j^2 = estimated variance of Y in each j -th stratum; S_j = standard deviation in each j -th stratum; $S_{\bar{Y}}^2$ = estimated variance of the stratified mean for a finite population; $S_{\bar{Y}}$ = standard error of the estimated mean; n = sample size to obtain a given precision; $E\%$ = sampling error in percentage (%); E = sampling error in absolute; 95% CI (ha) = confidence interval per hectare; 95% CI (stratum) = confidence interval per stratum; 95% CI (total) = confidence interval for the overall population; Table S1: Floristic composition, taxonomy and forest structure of Flona de Anauá, in southern Roraima, Brazil. * Where: $Trees_i$ = total number of individuals per species in the 30 hectares of the forest inventory (FI); D = density of individuals per species per hectare, $Trees\ ha^{-1}$; DBH = mean and standard deviation of diameter at breast height, in cm; TH = mean and standard deviation of total height, in meters; BA = basal area per species per hectare, in $m^2\ ha^{-1}$; V = commercial timber volume per species per hectare, in $m^3\ ha^{-1}$; AGB = aboveground dry biomass per species, in $Mg\ ha^{-1}$; BGB = belowground dry biomass per species, in $Mg\ ha^{-1}$; B = total dry biomass per species, in $Mg\ ha^{-1}$; Carbon: AGC = aboveground carbon per species, in $Mg\ ha^{-1}$; BGC = belowground carbon per species, in $Mg\ ha^{-1}$; C = total carbon per species, in $Mg\ ha^{-1}$.

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