EDAPHIC FACTORS AND FLOODING PERIODICITY DETERMINING FOREST TYPES IN A TOPOGRAPHIC GRADIENT IN THE NORTHERN BRAZILIAN AMAZONIA

Abstract

The Brazilian Amazonia is a region covered by an extensive mosaic of tropical forests conditioned by different topographical and hydro-edaphic features. Although studies relating environmental determinants of structure and floristic composition are systematically evolving in the region, there is no doubt that there are still information gaps due to the lack of research in peripheric areas of the Amazonia. The seasonally flooded areas of the state of Roraima situated on rio Branco-rio Negro basin, northern Brazilian Amazonia, still are deprived of such information. In this way, this work had as objective determine the physical and soil chemical attributes, and the flooding periodicity that characterize different forest types dispersed in a topographic gradient located in an area on the north of rio Branco-rio Negro basin. Soil samples (0-60 cm) were collected along a 2.7 km transect (31.1-64.8 m a.s.l.) crossing three different forest types: (i) mosaic between treed and forested shade-loving (La+Ld), (ii) area of ecological tension between forested shade-loving and open ombrophilous forest (LO) and (iii) open ombrophilous forest (Ab+As). The results indicated different soil classes and flooding periodicity for each forest type observed: Entisols Fluvents (La+Ld, 3-4 months flooded), Entisols Quartzipsamments (LO, 1-2 months) and Yellow Ultisols (Ab+As, no flooding). All analyzed soils were defined as nutrient-poor areas, especially those located on low altitude, characterized for higher hydrological restrictions (seasonal flooding) aggregating forest types of lower structural patterns (e.g. La+Ld). Soils on low altitude were also characterized as those with the highest percentage of fine sand and silt, while soil free of seasonal flooding (Yellow Ultisols) presented the highest levels of clay and coarse sand, always associated with the ombrophilous forests (higher structural patterns). These results improve our understanding of the environmental factors conditioning different forest types in this peripheral region of Amazonia, suggesting that ecosystems with higher hydro-edaphic restrictions are a strong indicator of forest types with lower structural patterns.

Keywords: oligotrophic ecosystems, water table, ecotone, phytophysiognomy.

INTRODUCTION

The Amazon basin occupies ~40% of the surface of South America and about 60% is inserted within the Brazilian territory [1]. Its predominant covering is defined as dense and open ombrophilous forests [2-3], but throughout the Amazonian biome there are many different forest types that may be distinguished by their floristic composition and structure due to the large environmental heterogeneity [4-5]. In general, the factors modeling the different forest types are attributed mainly to the climatic variations, hydro-edaphic conditions, topography, and anthropogenic interferences, all interacting and acting at different spatial scales [6-9]. This congregation of factors generates different structural and floristic shades with different ecosystem values, but generally information on the weight of each one, in the local and regional context, is little known due to the gigantism of the Amazonia, which makes sampling in peripheral areas a difficult process [3,10]. However, this kind of information is the basis for improving our knowledge on specialization of the various Amazonian phytophysiognomies, with different structural patterns and species diversity, directly influencing the estimates of biomass/carbon stocks and fluxes in this region considered to be the largest and most important "natural environment" mitigating the harmful effects of global climate change [11-12].

Although studies involving edaphic and hydrological factors in association with topographic gradients related to the dynamics of ecosystems have evolved rapidly in the Amazon [14-16], there is still a great lack of information due to huge regional gaps with rare scientific investigations. In this context, ecotone forests (transition areas, contact zones or areas of ecological tension) are ecoregions representing about 15% of the biome [17] but still have a lack of knowledge about the processes of their formation and maintenance [18]. These ecoregions are characterized by mosaics of different forest types condensed into distinct spatial scales that hamper their floristic and structural characterization and, above all, biomass/carbon estimates [19, 20]. This scarcity is mainly detected in the northern of the Brazilian Amazonia, especially in the seasonally flooded areas of the rio Branco-rio Negro basin located in the state of Roraima [16, 21-22].

Recent works have demonstrated that the ecosystems which form the mosaic of landscapes in this region present a direct integration between the plant cover and the physical, chemical and biological attributes of the soil [23] due to essential processes related to the biogeochemical cycles, water table outcrops, accumulation and decomposition of organic matter [16, 24]. This is a strong indication that environmental conditions associated with temporal flooding, sediment drag, and nutrient leaching may have high importance in the formatting of different forest types in this peripheral region of the Amazonia [25-27]. In the same context, the physical and chemical attributes of the soil, altitude, flooding periodicity, drainage and microclimate also considered as important determinants in the formation of different natural environments with specific structural patterns [28-29].

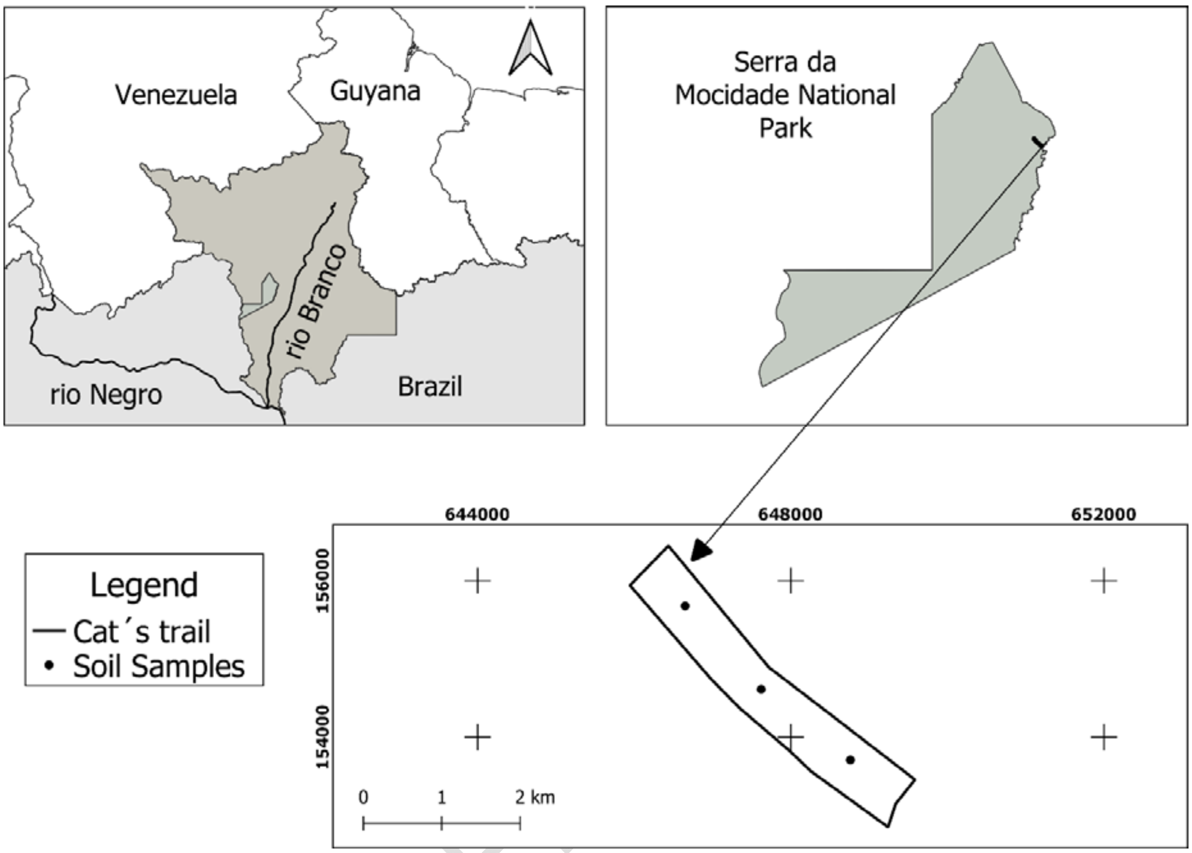
The objective of this study was to determine the flooding periodicity and the physical and soil chemical attributes that characterize a topographic gradient established between the Água Boa do Univini River and the Cumaru Mountain, a peripheral area of the Rio Branco-Rio Negro basin. This region belongs to the Serra da Mocidade National Park, a federal protected area located in the state of Roraima, northern Brazilian Amazonia. This region is formed by a large mosaic of forest and non-forest ecosystems without rare scientific investigations about the role of hydro-edaphic factors as determinants of different phytophysiognomies formations. Our results aim to improve the understanding of the environmental factors that determine different forest types in this region of Amazonia, indicating the association between environments with higher/lower hydro-edaphic restrictions and their respective forest structural pattern taking into account horizontal (stem diameter) and vertical (total height) parameters.

MATERIALS AND METHODS

Study area

This study was carried out in the Serra da Mocidade National Park (1.405º N - 61.648º W and 1.382º N - 61.673º W), a federal protected area managed by ICMBio (Chico Mendes Institute for Biodiversity and Conservation), located in the municipality of Caracaraí, ~ 290 km south of Boa Vista, capital of Roraima. The sampling area is characterized by ecotone zones (area of ecological tension or transition area or contact zone) between seasonally flooded forests under strong influence of the Água Nova do Univini river (black water) in association with open ombrophilous forests that reach the first steps of elevation of the Cumaru Mountain (Figure 1). The phytophysiological characterization, edaphic and flood periodicity were performed in a topographic gradient (31.1-64.8 m a.s.l.) inserted in an irregular transect (2.7 km long) known as "Cat's Trail", which begins on the right bank of the Água Boa do Univini river to the first steps of the northeast sector of the Cumaru Mountain, located at the northeastern end of the National Park (Figure 1).

Figure 1 - Study area indicating the geographical location of the Serra da Mocidade National Park and the soil profiles sampled along the Cat's Trail.



Characterization of the study area

The National Park is totally inserted in the rainy tropical monsoon type (Am) following Köppen classification, with annual rainfall of 1700-2000 mm and May-August representing the rainiest period (~40% of annual rainfall [30-31]. This region is marked by a chain of mountains that lends its name (Serra da Mocidade), resulting from the erosion of the Guyanese Craton, a large continental block formed by magmatic and metamorphic rocks dated between 1.8-2.5 billion years, in the Lower Pre-Cambrian period [32]. The characteristics of the main soil types in the National Park region are defined from lithological residues of the same geological constitution of the rock formation complex of the Serra da Mocidade, being a large residual mass, with an altitude reaching ~1.800 m, characterized by sharp crests and ravine slopes, covered by high altitude forests that lose this characteristic when reaching the zones of flooded forests of low altitude and smaller biometric structural patterns. Along this rocky complex, eight different soil classes can be found: Neossolo Flúvico (Entisols Fluvents), Neossolo Quartzarênico (Entisols Quartzipsamments), Espodossolo Humilúvico (Spodosols), Latossolo Amarelo (Yellow Oxisols), Gleissolo Háplico (Entsols), Latossolo Vermelho (Red Oxisols), Neossolo Litólico (Entsols Lithic) and Argissolo Amarelo (Yellow Ultisols) [32-33].

Phyto-characterization and periodicity of flooding

In order to carry out the phytophysionomic classification of the forest types in the sample area, we adopted the criteria proposed by the Brazilian Vegetation Classification System [34], based on a forest inventory carried out along the entire transect at Cat's Trail (R. I. Barbosa, personal communication). In this survey, the structure (horizontal and vertical) and arboreal groups (trees and palms) with stem diameter ≥ 10 cm were defined in each forest type arranged along the topographic gradient (31,1-64, 8 m a.s.l.). The flood periodicity data were obtained from observations performed in two consecutive rainy periods (2016 and 2017), where the sampling transect was coursed from start to finish in both periods, estimating a mean time interval (months) of flooding for each of them. All information was aggregated into an ecosystem conceptual model that faithfully followed the observed topographic gradient. Later, this model was adopted as an associative basis of the chemical and soil physical characteristics under each defined forest type.

Soil sampling and physical/chemical analyzes

In order to analyze and describe the physical and chemical attributes of the soil, three profiles (1m wide, 1m long, 80cm deep) were opened for each forest type considered. Soil samples were collected at 0-20cm, 20-40cm and 40-60cm depths. After that, the samples were deposited in plastic bags and identified by forest type and depth. All samples were air dried (TFSA), sieved (2 mm) and sent to the Soil Laboratory for physical (% sand,% silt and% clay) and chemical (pH, organic matter, exchangeable acidity, potential acidity, Ca, Mg, K, P, Cu, Zn, Fe, Mn and B) analysis following the methodology specified [35]. The descriptive classification of the soils sampled was performed by the Brazilian Soil Classification System [36] up to the third categorical level and correlated to the Soil Taxonomy [33]. The authorization number issued by the Chico Mendes Institute for the Conservation of Biodiversity for the conduct of this study was: (Authorization SISBEn, 54221-1)

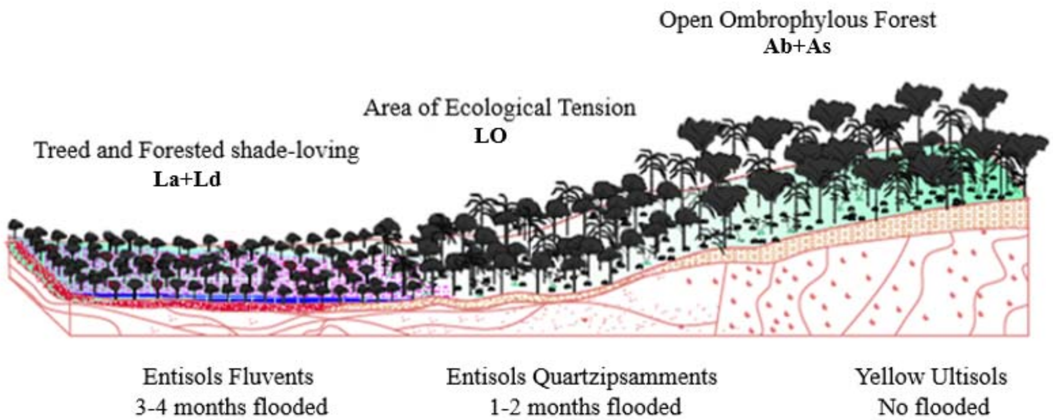
RESULTS AND DISCUSSION

The three profiles open along the sampled transect of the Serra da Mocidade National Park delimited three different types of soils: (i) Entisols Fluvents, (ii) Entisols Quartzipsamments and (iii) Yellow Ultisols (Figure 2). All of them were characterized as chemically poor (Table 1) and with high sand contents (Table 2). The results found in the forest type classified as Treed and Forested shade-loving (La + Ld), 3-4 month flooded in the year, are associated with the Entisols Fluvents, while Entisols Quartzipsamments and Yellow Ultisols are associated, respectively, to the Area of Ecological Tension (LO) and Open Ombrophylous Forest (Ab+As) (Table 3). These hydro-edaphic characteristics are similar to those reported in the Viruá National Park [21-22], a region with similar ecological characteristics to the Serra da Mocidade, strongly indicating that soils with higher levels of sand, low nutrient contents and higher flooding periodicity can define oligotrophic forest types with lower structural patterns (vertical and horizontal), in counterpoint to areas free of flooding processes, such as ombrophilous forests (Figure 3).

Figure 2- Soil profiles opened in the Serra da Mocidade National Park.

Where the profiles area: **A**= Entisols Fluvents (Treed and Forested shade-loving La+Ld) **B**= Entisols Quartzipsamments (Area of Ecological Tension LO) and **C**= Yellow Ultisols (Open Ombrophylous Forest Ab+As).

Figure 3- Conceptual model of the three forest types characterized by the soil classes and flooding periodicity in a transect in the Serra da Mocidade National Park, northern Brazilian Amazonia.



Entisols Fluvents can be considered as a low developed soil formed by quaternary sediment deposits, where drainage varies from moderate to imperfect, and it is very influenced by the outflow of the water table [37]. In the study area, this soil class was characterized by the predominance of high levels of fine sand followed by the silt (Table 2), associated with mosaics of treed and forested shade-loving, which are oligotrophic forest environments with low structural expression that naturally dominate part of the rio Branc-rio Negro basin [38-40]. The pH in this environment showed a tendency to reduce as a function of soil depth, due to the high levels of fine sand, which facilitates the processes of water percolation and nutrient leaching [41]. The available phosphorus also presented a decrease with depth, being this a process associated to alluvial sediment entrainment condition of the high parts of the topographic gradient, considering that the parts of lower altitude are characterized by more restrictive soils (3-4 months flooded) that may eventually accumulate higher levels of fertility in the early layers in contrast with deeper layers [26].

Our sampling in the profile of this soil class indicated that the organic matter had the highest values in the first sampling layer (0-20 cm). This result is in agreement with that presented [25-42], where the authors suggest that soils with higher elevations tend to have higher clay contents compared to lowland soils, but the organic matter contents are higher in the first layers of lowland soils due to the strong drag provided by the topography of terrain. Concerning to the physical properties of this soil class situated in the La+Ld forest type, it was verified higher concentrations of silt and fine sand, which are textural particles fully compatible with natural lowland environment [43].

Entisols Quartzipsamments is characterized as a soil under Area of Ecological Tension (LO), 1-2 months flooded in the year, and it can be described as a soil class extremely weathered, much quartzous, where almost all the clay is destroyed by acidolysis, or sandy deposits formed by wind phenomena, occurring in flat reliefs or basin reliefs or even in soft undulating reliefs [36-37]. This class of soil presented high levels of fine and coarse sand (Table 2), where these physical characteristics are associated to the formation processes of this environment, especially by the presence of small streams that precede the first undulating steps of the Cumaru Mountain, with undulations which aid the accumulation of alluvial material derived from the highest part. Thus, this soil type is related to the hydrological processes of sediment trapping, as also observed in the region of the National Park of Viruá (Roraima), in similar environments to those found in Serra da Mocidade [21].

The pH values determined for this soil class in the study area are in line with the standards [35]. An analysis along the soil profile in this forest type allowed to understand that there is a slight increase in the pH values from the most superficial layer (0-20cm) to the deepest ones (20-40cm, 40-60cm) and, consequently, a reduction in exchangeable and potential acidity (Table 1). This is a process fed by the infiltration of exchangeable bases or increase of organic matter, as previously established [44]. Likewise, the values of available phosphorus presented a decrease between the second (20-40 cm) and the third layer (40-60 cm), being a strong indicative of the reduction of this element along the vertical soil profile, as observed [45].and it can act as a limiting element in the larger / smaller vertical and horizontal structuring of the forest.

Organic matter also declines from the superficial to the deeper layers of this soil class in the study area. This same observation was reported in the Viruá National Park, with the authors suggesting that the topography of the terrain, especially those with soft ripples, may retain organic matter in the superficial layers of the soil due to the sediment trapping or the temporal outcropping of the water table [21] which are the same environmental characteristics observed in the ecotone (LO) of the Cat's Trail. In the same sense of the organic matter, the CEC also has a reduction pattern from the most superficial to the deepest layers, presenting a CEC saturation problem with the exchangeable Al, being common in this soil type, which can be aggravated by depth due to the decrease of organic matter in the soil and exchangeable bases such as Ca^{2+}, Mg^{2+}

and K^+, which would limit the development of the roots of the plants and affect the structure of the forest [46].

The Yellow Ultisols is characterized as a soil type flooding free, with strong presence of Open Ombrophylous Forest (Ab+As), with high contents of coarse sand and clay (Table 2) the formation factors of this soil class are similar to that of the Oxisols, with the same geomorphological characteristics and natural vegetation, but with a textural gradient [37]. The pH values found in this environment are slightly acidic and there is not much difference between the layers (Table 1). This process may be happening due to the absence of both water table outcrops and temporal flooding in this area [41-47]. The content of organic matter found in this soil type was high in the first layer, decreasing drastically towards the deeper layers. This result indicates a direct relationship with the CEC values found in this soil type, within the relational congruence [48] where organic matter and clays are the edaphic parameters with the greatest contribution to the formation of CEC values.

In this same analytical path, the concentrations of the micronutrients observed in the profile of this soil highlight the higher concentration of Fe in the first two layers (0-20 cm and 20-40 cm), being this element the main constituent of the structure of the clays [49]. This chemical characteristic was also observed in the ombrophilous forests of the Viruá National Park [23] suggesting that higher Fe contents in the ombrophilous forests of regions under the influence of treed and forested shade-loving mosaics may be due to the high presence of mineral particles (oxides of iron) derived from the organic matter deposited on the soil in litter form. This indicates that both Fe and the other micronutrients (Zn, Mn, B, Cu) have an important role in the nutrient cycling of this forest environment, but without a clearly defined role as a characterizer of forest types. This evidence the large range of uncertainties that still persist in the evaluations on the relationships between hydro-edaphic conditions and their role in the construction of Amazonian ecosystems. In this way, it is inferred that a better spatial distribution of the pedo-phytosociological studies, addressing peripheral regional gaps, can help us to generate environmental standards (topographic gradients, periodicity of flooding, soil classes) that more accurately configure the particular structural and floristic characteristics of different forest types, allowing better accuracy in biomass/carbon estimates, and giving the real importance of the Amazonia in the context of the global warming mitigation.

Table 1 - Chemical attributes determined in three profiles along a topographic gradient located in the Serra da Mocidade National Park, in the north of the Brazilian Amazonia in 2018.

Depth	pH	OM	P	Cu	Fe	Zn	Mn	B	K	Ca	Mg	H+Al	Al	SB	CEC	Sat. Bases	Sat. Al
(cm)	H_2O	g/kg	...mg/kg...						...cmolc/Kg...							V%	m%
Entisols Fluvents– Treed and Forested shade-loving (La+Ld)																	
0-20	5.1	14	3	6.80	92.00	8.20	3.00	0.43	0.10	0.20	0.10	3.40	0.20	0.40	3.80	11	33
20-40	5.2	7	2	6.70	37.20	8.05	1.40	0.25	0.06	0.10	0.10	2.80	0.20	0.26	3.06	9	43
40-60	4.8	5	2	4.60	14.20	5.80	1.10	0.24	0.06	0.10	0.10	2.50	0.20	0.26	2.76	9	43
Entisols Quartzipsamments – Area of Ecological Tension (LO)																	
0-20	4.6	23	3	1.60	9.80	5.65	15.40	0.26	0.20	0.30	0.10	6.40	0.40	0.60	7.00	9	40
20-40	4.9	9	3	2.10	18.60	3.80	2.40	0.38	0.15	0.30	0.10	4.20	0.30	0.55	4.75	12	35
40-60	4.9	5	2	2.00	19.00	3.60	1.20	0.35	0.13	0.30	0.10	3.80	0.20	0.53	4.33	12	27
Yellow Ultisols – Open Ombrophylous Forest (Ab+As)																	
0-20	4.6	11	3	2.90	106.00	5.95	6.50	0.34	0.15	0.60	0.20	4.70	0.20	0.95	5.65	17	17
20-40	4.7	5	2	2.10	102.00	4.30	1.90	0.32	0.12	0.20	0.10	3.40	0.30	0.42	3.82	11	42
40-60	4.6	5	1	0.70	80.00	3.45	2.00	0.27	0.06	0.10	0.10	3.40	0.20	0.26	3.66	7	43

Where: OM = organic matter, P = Phosphorus; Cu = Copper, Fe = Iron, Zn = Zinc, Mn = Manganese, B = Boron, K = Potassium, Ca = Calcium, Mg = Magnesium, H + Al = Acidable exchangeable, Al = Aluminium exchangeable, SB = Sum of bases, CEC =Cantionic Exchange Capacity, V = Saturation by Bases, m =Saturation by Aluminium.

Table 2 - Physical attributes determined in three profiles along a topographic gradient located in the Serra da Mocidade National Park, northern Brazilian Amazonia in 2018.

Depth (cm)	Arg	Sil	ArT	ArG	ArF
	...%...				
Entisols Fluvents – Treed and Forested shade-loving (La+Ld)					
0-20	13.9	19.1	67.0	7.0	60.0
20-40	14.2	16.8	69.0	4.0	65.0

40-60	14.2	16.8	69.0	4.0	65.0
Entisols Quartzipsamments – Area of Ecological Tension (LO)					
0-20	15.7	11.3	73.0	20.0	53.0
20-40	17.4	9.6	73.0	21.0	52.0
40-60	16.9	8.1	75.0	23.0	52.0
Yellow Ultisols – Open Ombrophylous Forest (Ab+As)					
0-20	15.4	3.6	81.0	51.0	30.0
20-40	20.3	6.7	73.0	42.0	31.0
40-60	25.0	6.0	69.0	37.0	32.0

Where: Arg Clay (<0.002mm), Sil Silt (0.053-0.002mm), Total ArT_Area, ArG_ Thick Sand (2.00-0.210mm), ArF_ Fine Sand (0.210-0.053mm).

Table 3 - Soil classes, flood periodicity and structural parameters (DBH and total height) of the forest types observed in the sampling transect formed by the Cat's Trail, Serra da Mocidade National Park. Where: La + Ld = Mosaic of treed and forested shade-loving; LO = Area of ecological tension between forested shade-loving and ombrophylous forest; Ab + As = open ombrophylous forest associated with the first steps of the Cumaru Mountain. Different uppercase (Trees, ANOVA followed by Tukey test) and lowercase (Palms; Test t) letters in the columns indicate discrepancies (α = 0.05) between the values of the taxonomic groups.

Forest Type	Density (ind ha^{-1})		DBH (cm)		Ht (m)	
	Trees	Palms	Trees	Palms	Trees	Palms
La+Ld	940	0	13.7± 3.3 A	-	12.2±2.3 A	-
LO	710	45	17.3± 7.4 B	14.5±3.5 a	17.7±2.7 B	17.5±1.9 a
Ab+As	423	85	20.9±12.9 C	18.5±6.5 b	18.3±4.0 B	16.6±3.2 a

(*) DBH = diameter at breast height (cm) and Ht = total height (m)

CONCLUSION

We conclude that each soil class determined in this study has a strong association with the topographic gradient sampled in the study area situated on Serra da Mocidade National Park, where lower altitude environments with larger flooding periods are related to forest types of lower structural pattern (e.g. treed and forested shade-loving) preferentially on oligotrophic soils (poor and sandy). These characteristics indicate the formation of environments influenced by continuous hydro-edaphic and geological processes, where seasonal flooding and sediment trawling are part of the process of formation of the main forest types in the study area. Therefore, edaphic factors and flooding periodicity are environmental characteristics that act as environmental filters wich are important in the formation of the landscape in this region of rio Branco-rio Negro basin. These results improve our understanding of the environmental factors that determine different forest types in this region of the Amazonia, where environments with higher hydro-edaphic restrictions are a strong indicator of forest types with lower vertical and horizontal structure.

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