Original Research Article

Analysis of the community structure of Diatoms (Bacillariophyta) in Roraima fluvial systems, Amazon – Brazil

ABSTRACT

The State of Roraima (Amazon - Brazil) is considered well-preserved from an environmental point of view, sheltering a great variety of rivers and forest and "*cerrado*" streams, with white (muddy), black and clear waters. From the identification of the planktonic community of diatoms, ecological indices and statistical analyzes were applied in order to determine the degree of abundance and species richness among the different ecosystems in the region. Qualitative and quantitative samples of phytoplankton were obtained during periods of low water (December to March), as well as measurements and analyzes of limnological parameters: water temperature (ºC), pH, dissolved oxygen (mg/L), oxygen saturation (%), transparency (m), total dissolved ions Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+} and Cl^-, total P and N (mg/L) and Chlorophyll-*a* (µg/L). A total of 172 plankton samples from 43 sampling points (20 in rivers and 23 in streams) were carried out. The low water period was characterized by slightly acidic to neutral pH, with low transparency and variations in conductivity and concentration of the ionic composition. The results indicated similarity in diatom composition between rivers and streams, with little heterogeneity in "*cerrado"* streams. Considering climate oscillation and spatial distribution, the PCA highlighted the parameters conductivity, dissolved ions, total P and chlorophyll-***a*** as preponderant to explain the behavior observed in the distribution of communities. For three components, the cumulative explanation was 68.6%. The ecological indices of richness and diversity indicated high similarity between rivers and streams, with good stability, homogeneity and ecological diversity for bacillariophytic diatoms. There were, however, some areas that, depending on the type of water and ionic concentration, showed some divergence in the composition of the diatom community. As environmental indicators, the diatoms showed that the water quality in the region is well-preserved, without eutrophication signals.

Keywords: Diatoms; abundance; frequence; richness; diversity; PCA.

1. INTRODUCTION

Since they emerged around 250 million years ago, bacillariophytes have spread across the planet, becoming abundant in aquatic ecosystems and wet soils. This highly cosmopolitan group may be associated with other organisms, remaining distributed throughout the water column and surface sediment. Diatoms represent one of the main groups of primary producers in aquatic ecosystems [1], presenting evolutionary characteristics that made them tolerant to a wide range of pH, salinity and ionic composition [2,3]. An important evolutionary factor for most planktonic diatoms is the ability of the cells to settle, considering that these organisms are denser than other phytoplanktonic groups. Sedimentation can be considered an important evolutionary strategy for diatoms, allowing the organisms to come into direct contact with the source of minerals and ions present in the bottom sediment, especially carbonates and silicates. In addition, the excessive storage capacity of phosphorus by this group (luxury consumption), which has already been well documented in research, allows its establishment both in eutrophic environments and in oligotrophic systems.

The great resistance of the group associated with the ability to adapt throughout the water column, from the epilimnion to benthic or epilithic organisms, allowed diatoms to be distributed in almost all aquatic systems on the planet. Another important aspect of this group is its use as a biological indicator of water quality [3-6]. Especially due to their ability to store large volumes of phosphorus, diatoms have been important in the assessment of the nutritional status of aquatic ecosystems, with a good indication for environmental eutrophication processes [6-9].

The hydrological cycle (rainfall etc.) and the natural circulation of water significantly interfere in the structure and dynamics of phytoplanktonic communities. Diatoms have a strong interaction with abiotic factors, both seasonally and spatially, and for this reason they are an excellent element for calculating ecological attributes. The community is an important tool for understanding the maintenance of diversity and species richness, and can be used to quantify and express the complexity of a given region [10,11]. According to McCann [12], the influence of species richness has been increasingly recognized over the dynamics and functioning of the community, especially in relation to stability and productivity, essential for understanding the factors that drive the phytoplankton richness.

Knowledge on the interactions diatoms establishes with environmental factors is important for the investigation of the role this community plays in the structuring of aquatic ecosystems. In addition to its importance within the Amazon Biome, the State of Roraima stands out for having a large number of indigenous reserves and environmental conservation units. Despite this, in addition to the natural growth of the municipalities, the region has been the target of interest for the implementation of hydroelectric plants, logging and mining. This research aimed to analyze the structure and dynamics of the diatom (Bacillariophyta) community through the application of ecological attributes, which allow identifying the water quality in this intense and complex system of rivers and streams.

2. MATHERIAL AND METHODS

2.1 Study Area

The State of Roraima is situated on a borderline with Venezuela (N-NW) and Guyana to the east, and with the states of Amazonas and Pará to the south. Especially in the N-NW axis of the State, there is a high indigenous contingent and many protected areas, with diverse conservation units [13,14]. This makes Roraima one of the most preserved states in the Brazilian Amazon. The study area comprised the sub-regions of the municipalities of Boa Vista (state capital; 2°49′10″N, 60°40′17″W); Alto Alegre (2°53′53″N, 61°29′ 29″W); Mucajaí (2°25'48"N, 60°55'11"W); Iracema (2°10'48"N, 61°02'24"W) and Cantá (02º36'18"N, 60º34'01"W) (Fig. 1). The average altitude of the municipalities is 70 meters above level sea. The predominant climate in the region studied according to the Köppen-Geiger classification is Tropical Equatorial "*Af*", with emphasis on Tropical Savanna "*Aw*" with summer rains from the northern portion to the east of the state. The average annual rainfall is 1,500 mm, and in the mountainous areas to the north the average rainfall can exceed 2,500 mm (Fig. 2).

The study area has a wide variety of reliefs and geological domains, including mountains with escarpments, valleys, plains and plateaus surfaces, several streams and waterfalls, and important aquifer recharge areas. The predominant watershed in the region is the Branco River, which covers 80% of the state's territory. With 1,300 km in length (Tab. 1), the Branco River is considered the main tributary (sub-basin) of the Negro River, contributing with one third of its flow and drainage area. Most of the headwaters of the Branco River are located in the mountain range between Venezuela and Guyana, in Yanomami Indigenous Lands and in the Raposa Serra do Sol reserve. The highest points in the Brazilian territory are located in this region, such as Monte Roraima (2,734 m), Serra do Sol (2,110 m) and Monte Caburaí (1,456 m) [15]. The largest contribution by volume to the formation of the Branco River occurs at the confluence of the Uraricoera and Tacutu Rivers, on the N-NE axis, 30 km north of Boa Vista. Its flow varies seasonally from 1,189 m^3/s between December and March to 5,205 m^3/s between May and September.

In the monitored area, Branco River can be subdivided according to the type of vegetation into three segments: Upper Branco River – over 170 km long, quite wide, shallow, with numerous sandbars and predominance of savannas, with features ranging from forest to countryside, made up mostly of grassy fields with scattered trees and palm trees; Medium Rio Branco – 24 km long, starting at the Bem-Querer waterfall to the district of Vista Alegre. It is a transition area with several riffles full of stone, making the stretch not navigable for large boats, and presence of savannas, buritizais, muricizeiros, paricaranas, grasses and open rainforest. The last segment or low Branco River has 388 km long towards the Center-South of Roraima until its mouth in the Negro River. It is a region of Dense Ombrophilous Forest, with marginal lakes and Campinaranas, typical vegetation of sandy and wet soils [15-17].

During the rainy season, the river water becomes muddy due to the transport and resuspension of sediments, being considered according to the classification of Sioli [18] as white water. In the dry periods, between December and March, the sedimentary load tends to precipitate, increasing transparency, and giving the river an appearance of clear water. It is in the dry periods that the peak of algal blooms in the system occurs.

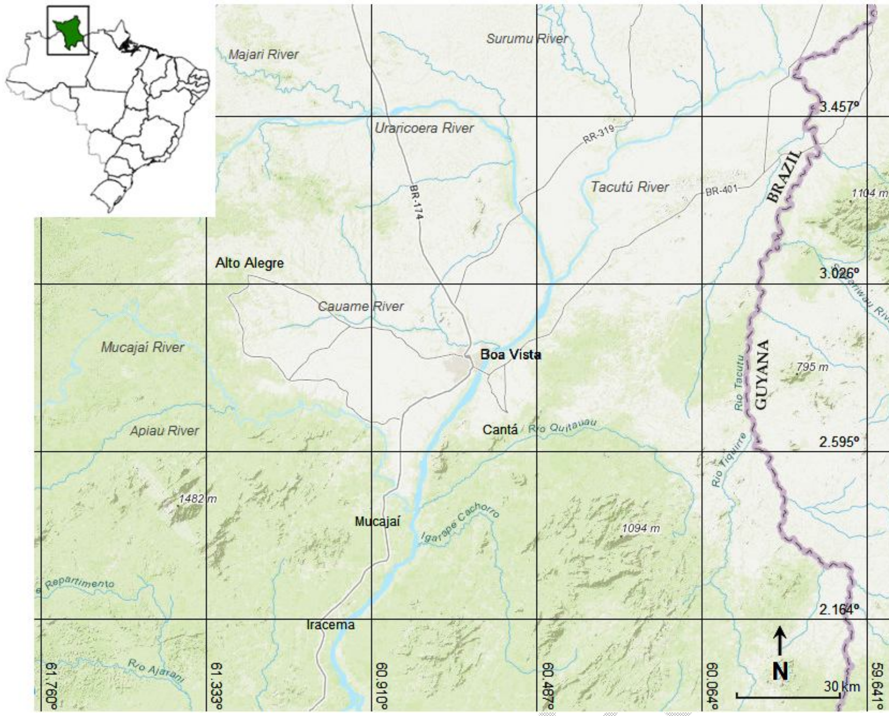

Figure 1. Study area with the location of the main river-stream system. Fonte: ArcGIS Web Application - © 2022 ArcGIS.

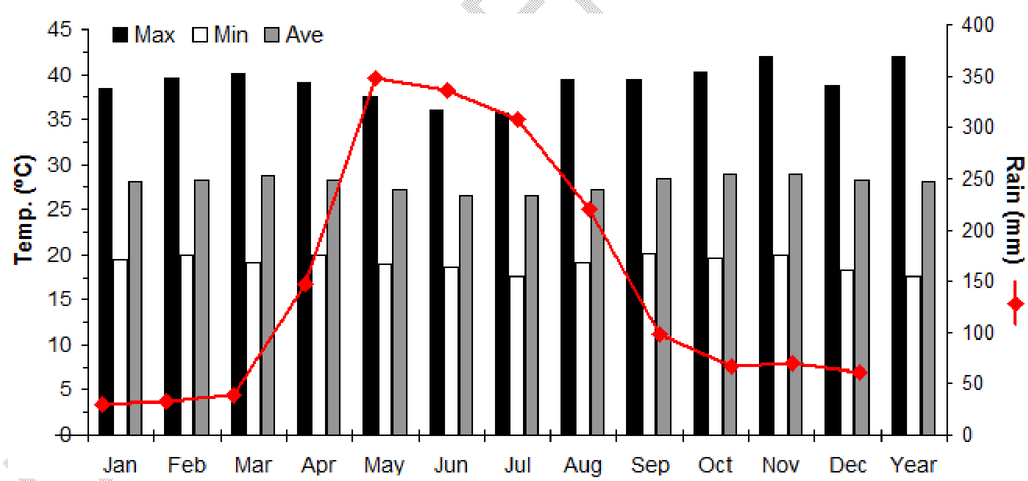

Figure 2. Temperature and rainfall monthly in Roraima State, Amazon – Brazil. Source: INMET (normal climatology from 1991-2022).

The Uraricoera River, with 735 km long (Tab. 1), runs a long stretch of riffles through dense and open forests, following its final course through the plains near Guyana. It is in this basin that the Maracá Island is located, in the Ecological Station of Maracá, considered the second-largest river island in the world. The Tacutu River with 371 km long (Tab. 1) has almost all of its drainage in the N-NE axis, an area dominated by savannas. The first section of the Tacutu goes north, and from its meeting with the Maú River it makes an abrupt turn to the southwest until it meets the Branco River. The Tacutu River basin is home to the Brazilian part of Monte Roraima with 2,875 meters. The Mucajaí River, with 504 km long, starts in the Serra do Urucuzeiro and follows the W-E axis in the municipality of Mucajaí, until it flows into the Branco River. The highest section of this basin is characterized by a great slope, with several waterfalls and riffles of relevant interest for the construction of hydroelectric plants, especially close to indigenous lands and FLONA of Roraima. The Lower Mucajaí River is a natural divider of the plowed area and forest, between the districts of Mucajaí and Boa Vista. Its flow varies seasonally of 271 m^3/s between December and March to 889 m^3/s between May and September, with a peak in July. [15-17,19]. The Cauamé and Quitauau Rivers should also be highlighted as important tributaries of the Branco River on the right and left banks, respectively.

2.2 Water quality

The State of Roraima is considered one of the best preserved in the North region of the country, due to the large number of conservation units. The studied region presents an immense mesh of sub-basins and streams, almost all of them well-preserved. Despite this, the absence or inadequacy of sewage work in the municipalities [19] can contribute to domestic sewage disposal into the fluvial system. The problem can be aggravated during the dry season, when the flow of the Branco River is five times lower than in the flood, reducing its purification capacity. Another activity of potential impact for the studied region is the mining activity. The regions of Alto Alegre, Iracema and Mucajaí have areas of interest for mining and extraction of sand and pebble for civil construction.

Table 1. Hydrological data of monitored rivers.

	River			
	Branco	Tacutu	Uraricoera	Mucajaí
Max flow (m^3/s)	6995	689	2740	1118
Min flow (m^3/s)	1006	4	604	223
Med flow (m^3/s)	2989	203	1381	553
Area (ha)	18,001,284			
Length (km)	1300	371	735	504

Source: [12,13]

2.3 Analytical Procedures

For this research, 172 plankton samples from 43 points distributed in six rivers were analyzed and reviewed: Branco (8), Uraricoera (3), Tacutu (2), Cauamé (2), Mucajaí (3) and Quitauau (2), and 23 streams, located in the municipal areas of Boa Vista, Alto Alegre, Mucujaí, Iracema and Cantá (State of Roraima).

Plankton samples were collected during low water periods, between December and March and preferably in the morning, with a collection interval between 9:00 am and 3:00 pm. Qualitative and quantitative collections were performed according to the method described by Ütermohl

[20]. For the qualitative collections, the vertical and horizontal dragging method was applied, within the range of the euphotic light zone, with nylon nets 30 x 70 cm and mesh opening of 20 and 45 µm. For the quantitative collections, a five-liter Van Dorn bottle was used, and the water volume was transferred to 500 mL bottles and fixed with acid lugol. Periphyton and bottom sediments were also sampled and preserved with 1% acetic lugol's solution for analysis. All material collected was preserved in Transeau solution (1:1).

Morphological analysis and measurements used in taxonomic typing were performed with a Zeiss phase contrast binocular microscope with 25, 40 and 100x objectives, using lugol and/or methylene blue as contrast. The score of material was done with an inverted microscope and Sedwick-Rafter's sedimentation chambers of 5 mL volume. Cells, colonies and filaments were quantified according to random fields' method. Only individuals with intact plastids or with alterations resulting from fixation were quantified. Based on the minimum area method and considering the samples with the greatest number of species, the constant number of fields were counted (n=30). The score limit has been established according to the rarefaction curve of species, having been closed once reached the total of 100 individuals of the most common species. Cell volumes were calculated by approximating geometric shapes and calculating the respective volume (μm^3) [21]. Biomass was estimated by multiplying the densities of each taxon by the average volume of its cells or colonies (at least 10 individuals per taxon) and expressed by 1 mm^3/L equivalent to 1 mg/L [22].

The identification system for species classification was based on the recognition of phenotypic characters, including frustula morphology; symmetry, shape, measurement and structure of the valve and apices; general layout of the raphe; presence or absence of pores and the composition of striae and areolas. To identify genera and species identification keys were consulted and all nomenclature was revised based on the *AlgaeBase* electronic taxonomic system [23].

Limnological procedures were carried out in the field and water samples were collected for analysis of ionic composition and total nutrients. The measurements of water temperature (ºC), pH, dissolved oxygen (mg/L) and oxygen saturation (%) were performed directly in the environment, with a multiparameter probe Horiba - Water Quality Monitoring System U-20XD Series. The transparency (m) was measured with a Secchi disk (ϕ =30cm), from which the euphotic zone was calculated. The total dissolved ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+} and Cl^-, mg/L) were determined by atomic absorption spectrophotometry (methods: 3500-Na, K, Ca, Mg, Fe and 4500-Cl; [24]). Total phosphorus and nitrogen (mg/L) were determined by extraction and acid digestion (4500-N, P methods). Chlorophyll-*a* (Clh-*a* µg/L) was determined by the acetone extraction method (90%) on Whatman GF-F filters, and was determined by the colorimetric method (664 ηm), according to the procedures for biological analysis [10200 – Plankton] and [10300 – Periphyton] [24]. All sample collection, analysis and conservation procedures followed recommendations from the specialized literature [22,24,25].

2.4 Data analysis

For the analysis of the community structure, representation of taxa by class, order and family; relationship of presence and dominance of taxa in rivers and streams; distribution of taxa at sampling sites with the respective indication of presence and dominance; population density (D = ind/mL) calculated for a minimum sampling efficiency of 80% according to Weber [26]; relative abundance (R_a %) and total abundance (T_a %) calculated from the direct score of the organisms in the Sedwick-Rafter's chambers; total frequency (FT %) and frequency of occurrence (FO %) in rivers and streams calculated by the general equation F_O=a.100/A (where; a= number of samples that the taxa occurred, and A= total number of samples); Dajoz constancy index [27], defined as SD=(n/N)*100 (where n = number of samples in which the species occurs and N = total number of samples), categorized as Absent (0%) – Accidental (1-25%) - Accessory (26-50%) and Constant (51-100%); and species richness (S = total number found taxa) all were considered.

The definitions of abundance and dominance followed specific criteria established by [28]. Were defined as abundant in terms of relative biomass the taxa with contribution above 10% and dominant above 50%. The Margalef (S_G), Menhinick (S_N) and Odum (S_O) species richness index, the Jaccard index (S_J) and the Sörensen index (S_S) were calculated in accordance with the descriptor analysis [29,30]. The relationship between abiotic parameters and phytoplankton and phytoperiphyton was determined from Principal Component Analysis (PCA) with rotation varimax. The PCA was obtained from the Pearson moment-product correlation coefficient, with the matrix formed by the cell density of the phytoplankton species together with the environmental variables, and from the calculation of the eigenvectors and eigenvalues of the dispersion matrix. These analyze were performed with NTSYS (Numerical Taxonomy and Multivariate Analysis System) © Exeter Software (New York – USA); STATISTICA 7.0 © StatiSoft. Inc. 2004 (Tulsa, OK – USA) and Ecolog 5.0.5 © 1990-2016 Mauro J. Cavalcanti.

Maps with interpolation by kriging were prepared from cartographic bases made available by IBGE, ArcGIS Web Application – ©2022 and NASA SRTM raster, using the UTM projection (zone 20 North) and Datum Sirgas 2000, with numerical scales of 1:250,000 and 1:500,000. The results of absolute frequency of occurrence by family for rivers and streams were plotted on thematic maps, with the aim of identifying correlations between aquatic systems in terms of abundance of organisms.

3. RESULTS AND DISCUSSION

3.1 Limnological aspects

The State of Roraima is located in the extreme north of the Brazilian territory, with its lands drained mainly by the Branco River basin, whose main formers are the Uraricoera and Tacutu Rivers (Fig. 1), inserted in the largest continuous area of savannas in the Amazon [15,16]. In the monitored section, the Mucajaí River is its main tributary on the right bank of the basin, followed by the Cauamé River, which runs further north almost parallel to the Mucajaí River. The region is characterized by a great diversity of streams. According to Junk [31] these are streams that receive a lot of light, unlike traditional forest streams, which are intensely shaded. For this reason, these streams were recognized by the author as "cerrado streams". They can harbor a wide variety of organisms, and their biota is able to exist at very low concentrations of nutrients [31]. Considering that these streams form a complex connection network, with good lighting and nutritional support, the diversity of planktonic species is very representative in the region.

Table 2 summarizes the limnological results for the dry periods sampled. The results suggest that the studied rivers are classified as clear water rivers, according to the Sioli classification [18]. The pH ranging from slightly acidic to neutral (mean 6.26) and electrical conductivity between 7.5 and 22.3 μS_{25}/cm (mean 17.8 μS_{25}/cm) confirmed this trend (Tab. 2). The dry periods were marked by strong winds, which intensified the turbulence of the waters, resulting in greater oxygenation, especially in the epilimnion. On dissolved ions in rivers, most of the results indicated a ratio of 1:1 between Na and K and 2.5:1 between Ca and Mg. Sodium contents in rivers come mostly from silicates, which make up the local sedimentary system. Total iron varied from 0.12 to 1.52 mg/L (average 0.48 mg/L), with the highest punctual levels being observed in the Mucajaí River. These higher punctual levels of iron were due to the leaching process of the ferruginous crusts present in the sub-basin. Chloride ions varied in the rivers between 0.58 and 1.63 mg/L (average 0.91 mg/L), with higher levels in the Tacutu River, in the highest section monitored (Fig. 1). It is suggested that the highest concentrations of iron and chloride in the water are due to the weathering of rocks containing chlorite and clay minerals, both from areas of accentuated relief, with altitudes above 800 meters.

The monitored region presents a very irregular relief, with stretches of plain, slope areas with several riffles and waterfalls, and elevations that vary between 800 and 1,500 m. The irregularity of the relief with steep slopes has already drawn attention to studies aimed at local hydroelectric use, with an energetic-economic and socio-environmental focus, especially on the Branco River, where the stretch of riffles '*Bem Querer*' 130 km from Boa Vista (Fig. 1) and '*Paredão*' on the Mucajaí River are located. Phosphorus and total nitrogen contents varied homogeneously from 0.02 to 0.05 mgP/L and from 0.09 to 0.16 mgN/L. The distribution of nutrients in the monitored areas has as its main source the decomposition and remineralization of organic matter, since the phosphate and ammonia fractions represented more than 45% of the individual total of each element. Chlorophyll-***a*** levels in the basins varied between 1.5 and 2.5 µg/L, with the highest levels being observed in the Branco River, near the state capital.

The streams are differentiated ecosystems within the region's rivers and lakes complex. With a vast distribution network, the streams are physically, chemically and biologically different from each other, due to their geographical position within the environmental mosaic. In the N-NE axis, the streams present a white water pattern, with greater transport of suspended sediments from accentuated reliefs. In these sections, the transparency was generally below 0.5 meters and the conductivity ranged between 11 and 12.5 μS_{25}/cm. In the middle section, between the municipalities of Alto Alegre, Boa Vista and Mucajaí, the streams showed behavior of "cerrado" streams, little shaded, with greater water transparency and low electrical conductivity.

In the N-NW axis and especially to the south of the monitored area, the streams showed a pattern of forest streams, from clear to black water, with evidence of the presence of humic compounds, which in some cases directly interfered with the water's pH. Specifically, in the stretch between the municipalities of Iracema and Cantá, black water streams were observed that are part of the set of small sub-basins in northern Brazil, which supply the Negro River basin. In these streams, the pH was below 5, confirming the interference of humic compounds in the buffer system. The streams of the most western stretch, especially the sub-basins of the Cauamé and Mucajaí Rivers, come from a dense forested area of the Maracá Ecological Station (EE Maracá) and Roraima National Forest (Flona) reserves. In the district area of the municipality of Cantá, further south of the monitored area, there are several elevations ranging between 700 and 1,300 meters in altitude, which we can define as 'sea of hills'. In this stretch, there are streams of white waters due to the accentuated load of transported sediments, especially with the arrival of the rainy season in the region. The best example of this is the Cachorro Stream (Fig. 1).

Usually, the charge of dissolved ions in the streams was much lower than the concentration observed in the rivers. In the case of chloride ions, for example, the average value of Cl in the streams represented only 23% of the average concentration determined in the rivers. It can be said that in the streams, the tendency towards heterogeneity of the results was due to a set of associated climatic and geomorphological factors, including wind action, transported sediment load and insolation – shading of the water surface. In general, the slope in several parts of the region favored litter leaching during periods of intense rainfall, aided by the flooding process of the Várzea.

Table 2. Limnological parameters monitored in the rivers and streams of the Branco River basin region, Roraima – Amazon for the low water period.

	River			Stream		
	Med	Min	Max	Med	Min	Max
Secchi (m)	0.63	0.40	1.20	0.66	0.40	1.15
Temp (ºC)	27.95	25.40	28.50	27.2	26.8	27.7
pH	6.26	5.66	7.21	6.24	4.50	6.76
EC (μS_{25}/cm)	17.79	7.50	22.30	11.6	6.6	19.1
DO (mg/L)	7.78	6.20	9.50	7.3	7.0	7.7
Satur (%)	96.85	95.40	99.40	93.5	91.0	95.0

Na (mg/L)	1.63	0.42	2.10	0.79	0.73	0.85
K (mg/L)	1.14	0.44	1.58	0.65	0.56	0.72
Ca (mg/L)	1.67	0.26	2.62	0.76	0.72	0.81
Mg (mg/L)	0.73	0.09	1.32	0.42	0.36	0.51
Fe (mg/L)	0.48	0.12	1.52	0.75	0.68	0.85
Cl (mg/L)	0.91	0.58	1.63	0.68	0.63	0.72
N_{tot} (mg/L)	0.13	0.09	0.16	0.21	0.09	0.31
P_{tot} (mg/L)	0.04	0.02	0.05	0.02	0.01	0.03
Clh-*a* (µg/L)	1.75	1.52	2.48	0.40	0.30	0.55

3.2 Diatoms Community

69 taxa distributed in three Classes, 10 Orders, 15 Families, 20 Genera and eight Varieties were identified (Tab. 3). Bacillariophyceae class was predominant with an abundance of 89.9% in both rivers and streams. The most representative orders were Naviculales (37.7%) and Eunotiales (26.1%); and the most representative families were Eunotiaceae (26.1%) and Pinnulariaceae (18.8%). 15 taxa were considered dominant in the rivers: *Actinella* sp., *Aulacoseira ambígua* (Grunow) Simonsen, *A. granulata* (Ehrenberg) Simonsen, *Aulacoseira* sp., *Eunotia asterionelloides* Hustedt, *Eunotia zygodon*, *Frustulia rhomboides*, *Gomphonema gracile*, *Pinnularia acrosphaeria*, *P. braunii*, *Stauroneis anceps*, *Surirella biseriata*, *S. linearis*, *Synedra goulardii* var. fluviatilis (Lemmermann) Frenguelli and *Tabellaria fenestrata* (Lyngbye) Kützing. 14 taxa were considered dominant in the streams: *Actinella mirabilis*, *Aulacoseira ambigua*, *A. granulata*, *Aulacoseira* sp., *Cymbella amphicephala* Näegeli ex Kützing, *Eunotia didyma* Grunow ex Zimmermann, *E. flexuosa*, *E. serra*, *Frustulia rhomboides*, *Neidium affine*, *N. bisulcatum*, *Rhizosolenia eriensis* H.L.Smith [*Urosolenia eriensis* (H.L.Smith) Round & R.M.Crawford], *R. longiseta* O.Zacharias [*Urosolenia longiseta* (O.Zacharias) Edlund & Stoermer] and *Surirella linearis*.

Table 3. Classification of the 69 taxa identified.

Class	Order	Family	Genera	Variety
Bacillariophyceae	*Anaulales*	*Amphipleuraceae*	*Actinella*	mucophila
Coscinodiscophyceae	*Aulacoseirales*	*Anaulaceae*	*Aulacoseira*	claviculata
Mediophyceae	*Bacillariales*	*Aulacoseiraceae*	*Cymbella*	didyma
	Cymbellales	*Bacillariaceae*	*Desmogonium*	elongata
	Eunotiales	*Cymbellaceae*	*Eunotia*	crassinervia
	Fragilariales	*Eunotiaceae*	*Fragilaria*	saxonica
	Naviculales	*Fragilariaceae*	*Frustulia*	legumen
	Rhabdonematales	*Gomphonemataceae*	*Gomphonema*	fluviatilis
	Rhizosoleniales	*Naviculaceae*	*Gyrosigma*	
	Surirellales	*Neidiaceae*	*Navicula*	
		Pinnulariaceae	*Neidium*	

		Rhizosoleniaceae	*Nitzschia*	
		Stauroneidaceae	*Pinnularia*	
		Surirellaceae	*Rhizosolenia*	
		Tabellariaceae	*Stauroneis*	
			Stenopterobia	
			Surirella	
			Synedra	
			Tabellaria	
			Terpsinoë	
3	10	15	20	8

Uniformity was more visible among the families present in the sampled rivers, especially *Pinnularuaceae, Eunotiaceae* and *Aulacoseiraceae* (Fig. 3A). The *Eunotiaceae* family had a percentage of presence ranging between 30.8 and 41.9% in all rivers, with the exception of the Cauamé River, where the rate was 23.1%. Between the *Pinnularuaceae* taxa, the lowest percentage of presence occurred in the Uraricoera River (10.8%). In the other rivers, the presence rate varied between 14.9% on the Mucajaí River and 22.7% on the Quitauau River. Among the organisms of the *Aulacoseiraceae* family, the percentages in the rivers varied from 7.9% in the Mucajaí River to 15.4% in the Tacutú and Cauamé Rivers. The same pattern of uniformity was not as evident among the sampled streams. This is explained because the streams were grouped within municipal sub-regions (Boa Vista, Alto Alegre, Mucajaí, Iracema and Cantá), often due to the difficulty of showing their geographic limits. Within the complex of streams studied, differences between physical and chemical parameters can be seen, highlighting pH, conductivity and ionic concentration. In addition, as already discussed in the description of the study area, white, black and clear water streams were identified, as well as forest and cerrado streams.

Among the forest streams, it was also possible to highlight differences between fully or partially shaded streams, which directly interfere with the incident radiation time and in the primary production of the system. The families that stood out with greater presence in the streams were *Eunotiaceae*, *Pinnulariaceae* and *Surirellaceae* (Fig.3B). In the *Eunotiaceae* family, the highlights of greater presence occurred among the streams present in the geographical area of the municipalities of Boa Vista (28.5%) and Alto Alegre (29.7%). Among the taxa of the *Pinnulariaceae* family, the highest percentage representations were observed in the regions of Cantá (26.0%), Boa Vista (24.9%) and Mucajaí (21.2%). For the *Surirellaceae* family, the highest percentages of presence were observed in the regions of Iracema (13.6%), Mucajaí (12.8%), Boa Vista and Alto Alegre, both with 11.4%. The dominance rate was much more representative between the taxa observed in the streams. In this respect, the families *Eunotiaceae* (44.4%), *Aulacoseiraceae* (32.6%), *Neidiaceae* (22.2%) and *Rhizosoleniaceae* (14.5%) stood out. As environmental conditions, such as light concentration, pH and nutrients vary from one system to another, the predominance of certain taxa is expected, and whose characteristics include greater resistance and resilience to physicochemical water oscillations.

Table 4 presents the results of the ecological attributes for the communities of the Bacillariophyta Division in the rivers and streams. The first results show that there is a good similarity in the distribution of taxa between the rivers and streams, with a significant consistency of frequency and abundance. Thus, no great discrepancy in values between the ecological indices calculated for the system was expected. In fact, the species richness indices of Margalef (S_G= 9.8 and 9.4), Menhinick (S_N= 2.3 and 2.1) and Odum (S_O= 9.9 and 9.6; Tab. 4) showed very similar trends for the lotic environments studied.

Another important point is that the biodiversity indices of Margalef and Odum were close to 10, for a ratio between richness and abundance of 67:851 in rivers and 66:986 in streams (taxon:Ind), suggesting good ecological diversity for diatoms of the Bacillariophyta Division. These indices represent an estimate of the community's biodiversity, based on the distribution of individuals of different species as a function of the total number of individuals analyzed. In other words, these indices increase numerically as the number of species is greater in relation to the total number of determined individuals. The species richness indices obtained in this study were quite significant when compared, for example, to the equivalent coefficients for the Madeira River basin, in the Western Amazon macro-region. In a study focused on the Cyanophyta Division, following the same methodological procedures, the authors obtained indices S_G= 1.5 and S_N= 1.0 for the low water period [32]. Subsequently, another study focusing on six divisions with 610 identified taxa, the Margalef and Menhinick indices obtained during the drought were S_G= 12.8 and S_N= 2.7 [33].

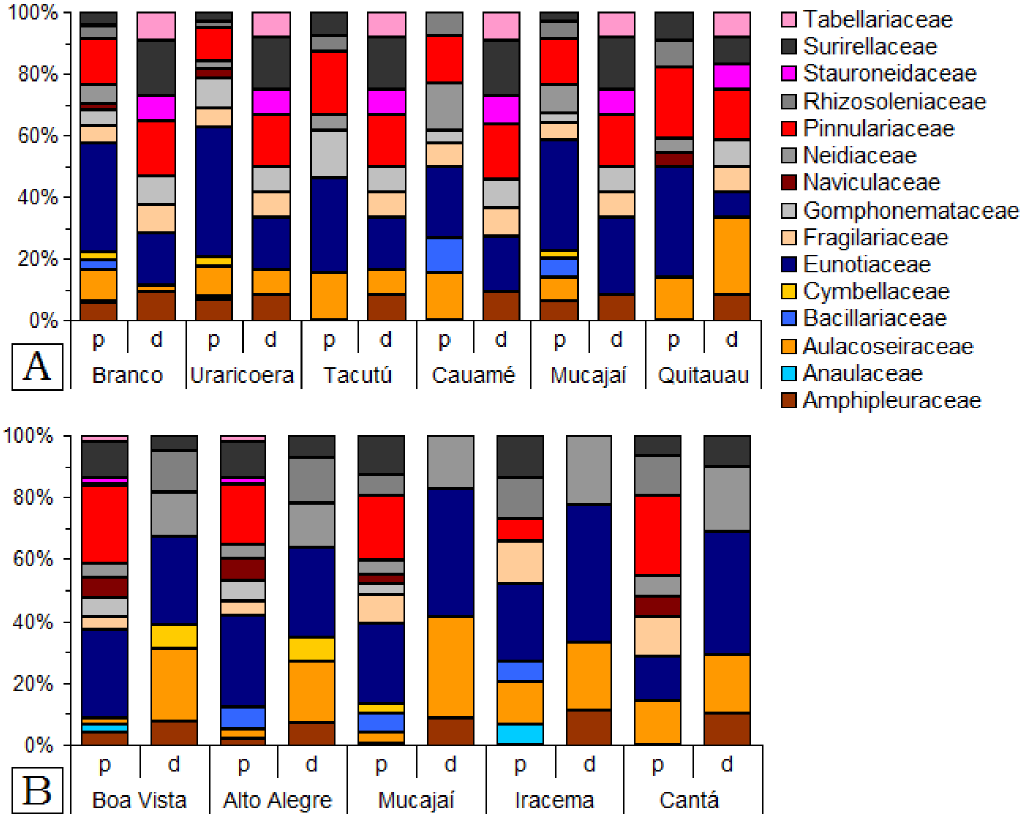

Figure 3. Presence (p) and dominancy (d) of taxa by family in the rivers (A) and streams (B) sampled.

Environmental factors that can directly affect species richness are isolation and area, latitudinal gradient, elevation, water depth and successional gradient [34]. Considering this aspect, the Branco River basin is very well-connected by an immense network of channels, which annually contribute to the homogenization of a large part of the system through the flooding of lowland areas (Várzea). The torrential and periodic rains that occur upstream of the basin, in the mountainous regions of the NW-NE axis, also contribute to the transport and mixing of waters in the ecosystem. The species representativeness indices of Jaccard (S_J= 0.84 and 0.80) and Sörensen (S_S= 0.91 and 0.89) presented values very close to each other and between the sampled environments. Developed as statistical tools to measure the similarity and diversity of sample sets, the results indicate two important aspects of a methodological and ecological nature.

From a methodological point of view, the similarity between the results suggests that the qualitative and quantitative sampling procedures adopted were satisfactory and representative. In the ecological aspect, the calculations suggest good similarity between the sets of pairs of rivers and streams, confirming the homogenization of the basin, or even indicating great similarity in the composition and relative abundance of the species of the communities. It should be noted that among the rivers the degree of significance of similarity was higher than 84% (S_J=

0.84) and in the streams 80% (S_J= 0.80). In the case of the streams, the existence of white, clear and black waters environments was confirmed through limnological parameters pH and conductivity. Despite this, there was consistency in the distribution of diatom species in the streams.

The results may also suggest that there is little or isolated anthropogenic interference in the system, so as not to cause significant disturbances in the balance of ecological diversity. Except for the points sampled within the urban areas of the municipalities, which eventually showed some indication of degradation due to the disposal of untreated domestic waste (sewers), the system, due to its very complexity, proved to be well-preserved. The knowledge of the spatial distribution of species richness is fundamental for the establishment of programs of restoration and/or ecological conservation, both in aquatic ecosystems as terrestrial. Although the indexes are a dimensionless numerical factor, which allows direct comparisons of results in different ecological systems, Magurran [30] suggests that ecosystems that are distinct from the point of view of environmental factors (latitude, elevation, depth, etc.) should not use the indexes as comparative parameters. For the author, the comparative analysis of diversity indices must take into account the respective sampling areas and their equivalences, otherwise, the rarefaction of data must be adopted in order to carry out an appropriate comparative analysis.

In general, diversity indices tend to demonstrate that the higher the specific richness found, the lower the values of dominance and equity in the composition of species diversity [35]. This trend to reduce the dominance cannot be proven in this study, because the pattern of ecological distribution was based on a single Division (Bacilariophyta diatoms).

Table 4. Ecological attributes apply to the analysis of the phytoplankton community structure in low water periods.

Ecol.att.	**Rivers**	**Streams**	**Basin**	Ecol.att.	**Rivers**	**Streams**	**Basin**
D (ind/mL)	141.8	162.3		S_G	9.8	9.4	9.0
A (nº ind)	851	986	1837	S_N	2.3	2.1	
R_a (%)	67	66	69	S_O	9.9	9.6	9.2
T_a (%)	46.3	53.7	100	S_J	0.84	0.80	
S_D (%)	46.33	53.67	100	S_S	0.91	0.89	
S (%)	67	66	69				

Were: D= density; A= abundance; R_a= relative abundance; T_a= total abundance; S_D= Dajoz constancy index; S= species richness; S_G= Margalef species richness index; Sn= Menhinick species richness index; S_O= Odum species richness index; S_J= Jaccard index; S_S= Sörensen index.

3.3 Statistical analysis

Based on the physical, physical-chemical and biological parameters, the PCA was developed, considering the spatial distribution (rivers and streams) and the climatic oscillations between the monitored drought periods. The analysis allowed to indicate the variables associated with each factor, and to determine the degree of association, identifying which variables were primarily responsible for the biological diversity and abundance of species of the Bacillariophyta Division, of phytoplankton and phytoperiphyton. In the analysis presented in Table 5, we chose to select three components to explain the behavior of the variables (parameters) measured. With a set of three components, the accumulated explanation was 68.6%. With the selection of two components, the percentage of accumulated explanation would be 56.2%. Above that, with the choice of four components, the explanation would reach 78.0%, but with dispersion of two factors (variables) between the selected components and without improvement in the correlation of Factor 2.

The variables that stood out to explain richness and abundance of Bacillariophyta species were conductivity, dissolved ions (Na, K, Ca and Mg), total P and chlorophyll-*a* (Fig. 4). The pH, which was decisive in the classification of streams into clear, black and white waters, was not highlighted globally in the analysis, only highlighted from the choice of four components (Factor 4). This is explained by the fact that in the rivers that make up the Branco River basin, including the "cerrado" streams as tributaries, the pH had small oscillation within the slightly acidic to neutral pattern (mean 6.37). A second analysis, considering the frequency of taxa by order and family, highlighting orders Eunotiales (26.1%) and Naviculales (37.7%), and families Eunotiaceae (26.1%) and Pinnulariaceae (18.8%), identified a similar behavior than previously observed, with emphasis on electrical conductivity, calcium, total phosphorus and chlorophyll-*a*. Calcium is preponderant in the construction of diatoms' shells, while phosphorus is primarily stored in excess for the growth of the community.

Table 5. Eigenvalues of correlation matrix and related statistics.

	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	7.04	44.00	7.04	44.00
2	2.00	12.52	9.04	56.52
3	1.93	12.04	10.97	68.56

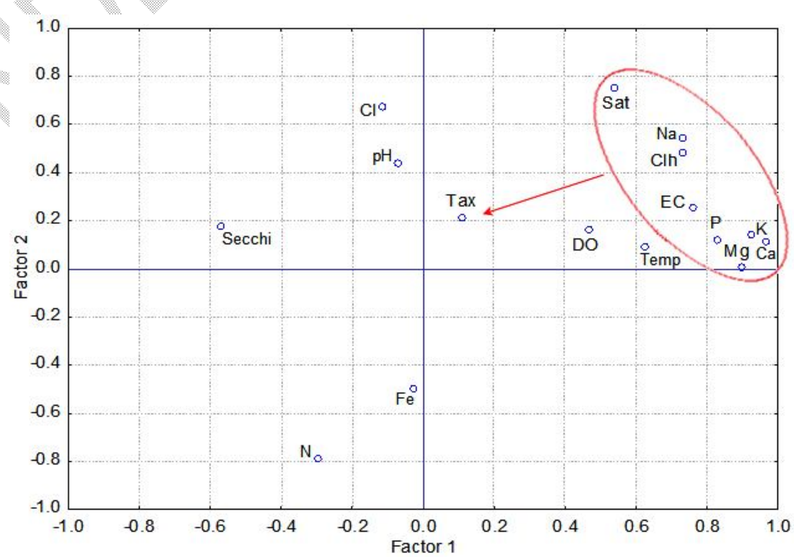

Figure 4. Factor 1 vs. Factor 2 with rotation Varimax row.

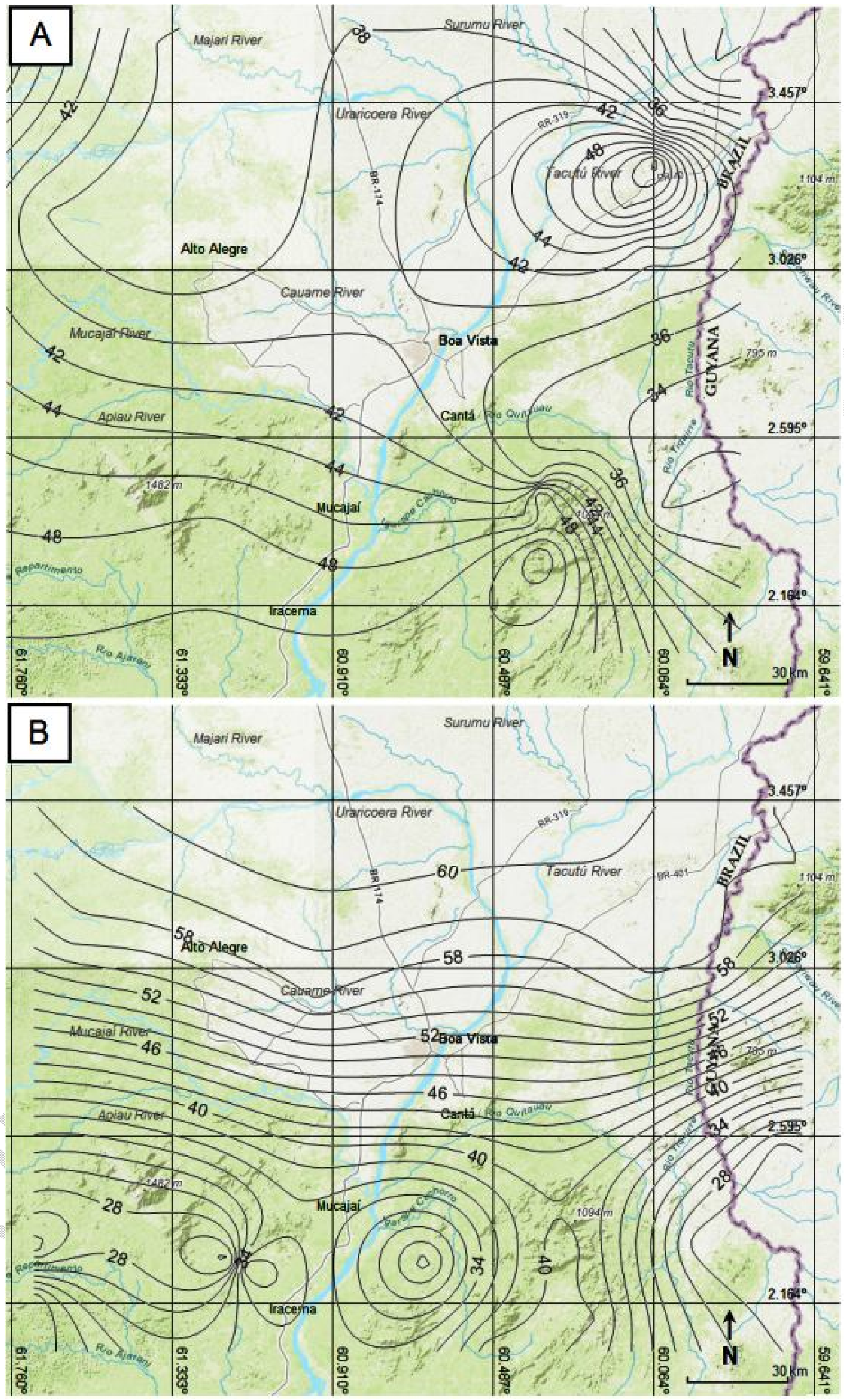

Figure 5. Absolute frequency of occurrence of Bacillariophyta Division taxa by family in rivers (A) and streams (B) monitored in the State of Roraima, Amazonia – Brazil.

The kriging interpolation analysis of the absolute frequency of occurrence of the planktonic organisms in the rivers and streams of Roraima suggests greater homogeneity in the distribution of taxa in the stream network, especially in the stretch between latitudes 2.5º and 3.0º North (Fig. 5B). In the fluvial network, the highest absolute occurrence frequency occurred in the northeast region of the municipality of Boa Vista and in the southeast region between the municipalities of Cantá and Iracema (Fig. 5A). In the northern area of the studied region, basically, forest streams can be found, shaded and with little variable pH and electrical conductivity. Only below the 2.5ºN quadrant "cerrado" streams were observed, with a greater degree of sunlight inside and pH variation. Among the rivers, the greatest divergences in limnological patterns were observed between the Tacutú and Uraricoera Rivers in the north and the Mucajaí River in the southwest of the State. This explains the frequency pattern observed in the interpolation.

CONCLUSION

Sixty-nine taxa distributed in three Classes, 10 Orders, 15 Families and 20 Genera were identified. The most representative families were *Eunotiaceae*, *Pinnulariaceae* and *Surirellaceae*, this especially in the streams. Geology, soil type and relief directly influenced the diversity and distribution of diatoms. In this aspect, the "cerrado" streams presented higher population density than the forest streams, whose amount of incident light is lower.

The use of ecological indices to describe the diversity of species proved to be a useful tool for the comparative analysis between the rivers and streams studied. The ecological indices of richness and diversity indicated high similarity between rivers and streams. There was similarity in the composition and distribution of taxa, with significant constancy of frequency and abundance of species. It was also verified that the richness indices were quite significant when compared to other Amazonian Rivers.

The PCA highlighted conductivity, Na^{+}, K^{+}, Ca^{2+} and Mg^{2+} ions, total P and chlorophyll-*a* as the most important variables to explain the richness and abundance of species in the Bacillariophyta Division. The pH was not considered in this analysis, although it was decisive to the classification of water (Sioli's classification) in the surveyed environments. Evolutionary strategies, such as the sedimentation capacity and the formation of statospores, allowed the development and wide distribution of diatoms in all analyzed environments, including water layers with a tendency to anoxia. Vertical circulation also contributed to the transport and distribution of cells between the epilimnion and hypolimnion, especially between the end of the ebb and the beginning of the flood, although this cycle works differently in small rivers and streams.

CONSENT

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ETHICAL APPROVAL

This section is not applicable in this manuscript.

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