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RESEARCH ARTICLE

Limnological characteristics and planktonic diversity of five tropical upland lakes from Brazilian Amazon

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Abstract – A limnological investigation involving physical, chemical and biological aspects was undertaken in five tropical upland lakes (Violão – Vl, Amendoim – Am, and Três Irmãs – TI1, TI2 and TI3) from Serra dos Carajás, Brazil. Results show that these lakes are shallow, weakly stratified, and of polymictic type. These characteristics may have caused vertical mixing of limnological parameters. Seasonal changes were minor for most parameters, except for chlorophyll-*a* (Chl-*a*) and cyanobacteria, which also showed considerable variation between lakes. In general, waters of these lakes were mostly acidic in nature (avg. pH 4.9–5.9), with high total Fe (up to 1.52 mg/L) and low electrolytic conductivity (avg. 8.13–14 μS/cm) and total phosphorus (TP) (avg. 10–35.5 μg/L). Although the water bodies have good quality and classified as class I and II types according to CONAMA Resolution No. 357/05, trophic state index (TSI) varies from ultra-oligotrophic to eutrophic state, with higher trophic state observed for Vl, TI1 and TI2. Limnological characteristics of these lakes is highly influenced by lithological and morphological parameters. Principal component analysis (PCA) reveals that Chl-*a* and cyanobacteria are not solely influenced by TP and lower concentrations of all these parameters in Am lake are probably due to specificities of its catchment lithology. Phytoplankton taxa in the lakes are characterized by small chroococcales groups and desmids together with filamentous algae, more commonly observed in the dry season. The zooplankton community in the lakes is mainly dominated by rotifers, followed by cladocerans and copepods. Regarding species richness, zooplankton was highest in Vl, while phytoplankton is highest in TI1, and this aspect is most likely related to lake water levels.

Keywords: limnology / water quality / phytoplankton / zooplankton / upland lakes / Serra dos Carajás

1 Introduction

The limnology of tropical lakes has become a high priority and draws major attention in the contemporary limnological research. This is particularly true for high mountain tropical lakes which are important freshwater ecosystems and likely the most comparable ecosystems across the world (Gunkel, 2000; Sahoo *et al.*, 2016). A comparison between lakes of tropical and temperate areas indicates that their limnology differs significantly due to variations in physical and chemical characteristics of waters such as temperature, thermal stratification, lake levels, light and nutrient availability (Lewis, 1987; Gunkel, 2000; Catalan and Rondón, 2016). These factors largely govern trophic state, phytoplankton assemblage as well as the planktonic growth of lakes (Reynolds *et al.*, 2002; Molisani *et al.*, 2010). Plankton is a sensitive and good indicator of changes in aquatic environment due to its rapid response to short time intervals, especially in the reproductive processes (Frisch *et al.*, 2012, Silva *et al.*, 2013). Thus, knowledge of the structure and functioning of these biological communities, and their interaction with the environment become essential for understanding the dynamic of these lakes (Huszar and Reynolds, 1997; Lopes *et al.*, 2011, 2014), as well as help in detecting any possible alteration in water quality (Diehl *et al.*, 2002; Chellappa *et al.*, 2009a; Molisani *et al.*, 2010).

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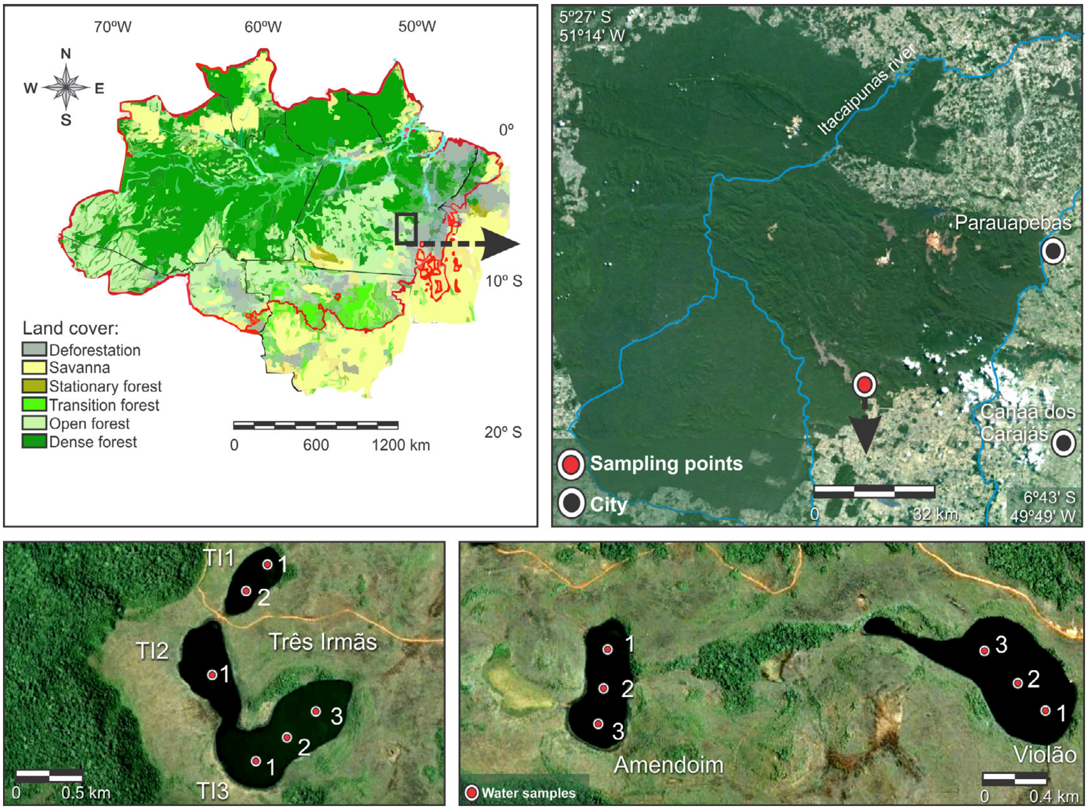

Fig. 1. Location map of the study area and sampling points of Violão, Amendoim, Três Irmãs lakes from Serra dos Carajás, PA, Brazil.

Tropical lakes serve as a crucial life support system by providing water for drinking, irrigation, and recreation opportunities such as fishing, boating and wildlife conservation. However, these lakes have been facing different challenges, such as eutrophication by nitrogen and phosphorus compounds, acidification and climate changes, which are the major causes of water quality degradation (Livingstone, 2003; Osborne, 2004; Hundey *et al.*, 2016; Catalan and Rondón, 2016). Effective monitoring of these lakes and their classification as per scientific norms and environmental laws are important aspects of lake's survey usable to establish freshwater's condition and long-term trends for effective management with the aim of achieving good water quality (Carlson, 1977; Burden and Malone, 1987; Buraschi *et al.*, 2005; Pasztaleniec and Poniewozik, 2010). A wide view of limnological classification has been proposed world-wide based on the morphology, physical, chemical and biological characteristics of waters (Häkanson and Jansson, 1983; Burden and Malone, 1987; Busch and Sly, 1992; Margaritora *et al.*, 2003; Rowan *et al.*, 2006; Skowron, 2009; Wang *et al.*, 2014). However, these efforts are still incipient for Brazilian lakes and missing for upland lakes of Amazonia. The Carajás province in Amazonia has some of the largest iron deposits of the world (Paradella *et al.*, 2015). In it, several upland lakes, which are hydrologically restricted and located at >650 m above mean sea level (amsl), formed over laterite crust by structural and degradation process (Maurity and Kotschoubey, 1995). These lakes are valuable sites for scientific research and for different water uses, besides providing habitat for flora and fauna and plankton species (Sahoo *et al.*, 2016; Lopes *et al.*, 2011; Guimarães *et al.*, 2017). However, though a few reports are available on hydro-biogeochemical characteristics (Sahoo *et al.*, 2016) and on plankton diversity (Lopes *et al.*, 2011), there is lack of data on the detailed limnological work of these lakes.

In this backdrop, the present survey was undertaken between 2013 and 2016 on five upland lakes of the Serra Sul dos Carajás based on the physical, chemical and microbiological characterization in waters, as well as plankton assemblages, which were monitored between 2011 and 2013. The aim of this study was to deepen the knowledge of the limnology of these lakes and to classify them based on their limnological characteristics.

2 Materials and methods

2.1 Study area and geology

Violão (Vl), Amendoim (Am) and Três Irmãs (TI1, TI2, and TI3) lakes (coordinate: 6.4° S, 50.4° W) are located in a plateau in the Serra Sul dos Carajás in SE Amazonia, Brazil around (Fig. 1). These lakes are hydrologically restricted and developed on a lateritic crust, which is covered by montane savanna vegetation and surrounded by Amazon rainforest (Fig. 1). Open forest and small patches of high-and-low forest can also be observed in central portions of the plateau over degraded crusts (Golder, 2010; Guimarães *et al.*, 2014). These laterites are extensively developed over banded iron formations (Silva *et al.*, 2009; Morais *et al.*, 2011).

Among these lakes, surficial water connection was observed in the TI lake system, but not in the case of Am and Vl lakes. Caves only occur in the catchment of Vl, with concentrated or dispersed occurrence of guano. Bird guano was also observed along the catchment of Vl. These guano occurrences and altered mafic rocks, which are found only in the northwestern portion of Vl Lake catchment, are potential source of phosphorous for Vl lake (Sahoo *et al.*, 2015). In contrast, caves and mafic rock outcrops were not observed around the catchment of the Am and, in results, P contents are low compared to Vl. Regarding Três Irmãs lake system, in the catchment of TI1 and TI3 there are locally thick soils related to iron-aluminous laterite (probably originated from metavolcanic rocks) whereas similar soils have not been noticed in the catchment of TI2. A tropical monsoon climate (Alvares *et al.*, 2014), with a mean annual temperature of around 26 °C and total annual rainfall ranges from 1800 to 2300 mm, with an average of around 1550 mm during the rainy season (November–May) and of *ca.* 350 mm during the "dry" season (June–October) (Moraes *et al.*, 2005), is observed in the studied region.

2.2 Sampling and analytical method

2.2.1 Limnological parameters

For limnological study, water samples were collected biannually in both rainy and dry seasons between 2013 and 2016. The monitoring points in each lake were chosen following their longitudinal profiles based on the bathymetric map and drainage patterns, which are presented in Figure 1. At each sampling point, three depths layered sampling (surface, middle and bottom of lake) was performed, except for TI2 (only surface) and TI1 (surface and bottom) because of their shallower water depth. Van Dorn water sampler was used to collect sample and then stored in HDPE and glass bottles following ABNT (1987) and SMEWW (2005). The inorganic, organic and bacteriological parameters were analyzed by using the SGS Geosol and Bureau Veritas analytical facilities following EPA (2004), SMEWW (2005) and CETESB (2006) guidelines. An overall precision, expressed as relative percent differences ($RPD = 100 \times (\text{duplicate } 1 - \text{duplicate } 2)/(\text{average of two duplicates})$), was obtained below 10% for all samples. Vertical profiles (at every meter from surface to the bottom) of water temperature, pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solid (TDS) were measured *in situ* using Horiba W-20XD multi sensor probe. Water transparency was measured with a Secchi disc (Secchi depth: Z_{Secchi}). Water quality classification was made using the Brazilian environmental regulation, National Environmental Council (CONAMA) Resolution No. 357/05 (Brasil, 2005). This classification ranges from class 1 to class 4 based on their water use and human consumption. The morphometric analysis of the lakes was conducted using Surfer software 13, Golden Software Incorporation, 2015.

2.2.2 Calculation of Water Quality Index (WQI)

Water Quality Index (WQI) was calculated following the equation established by Brown *et al.* (1970), using the weighted scores of a set of nine specific variables: temperature, pH, DO, biochemical oxygen demand (BOD), thermotolerant coliforms, dissolved inorganic nitrogen, total phosphorus (TP), total solids and turbidity. Each parameter is weighted by a value between 0 and 1 and the sum of all weights is 1 (CETESB, 2004–2006). WQI classification is as follows: Excellent: $79 < WQI \leq 100$; Good: $51 < WQI \leq 79$; Regular: $36 < WQI \leq 51$; Bad: $19 < WQI \leq 36$; Very bad: $WQI \leq 19$.

2.2.3 Calculation of Trophic State Index (TSI)

Trophic State Index (TSI) of the lakes was obtained by using the most recent modified Carlson Index, proposed by Lamparelli (2004), which has been widely considered as the most accurate and suitable method for the classification of the trophic state of trophic/subtrophic reservoirs (Molisani *et al.*, 2010). This index is based on three key variables, such as Chlorophyll-*a* (Chl-*a*), Secchi depth (Z_{secchi}), and TP. TSI is calculated based on the average concentrations of these patameters in each sampling period. The classification classes as follows (Molisani *et al.*, 2010)): $TSI \leq 47$, Ultra-oligotrophic; $47 < TSI \leq 52$, Oligotrophic; $52 < TSI \leq 59$, Mesotrophic; $59 < TSI \leq 63$, Eutrophic; $63 < TSI \leq 67$, Supereutrophic; and $TSI > 67$, Hyperutrophic.

2.3 Plankton community

The phytoplankton and zooplankton communities were sampled from the dry season of 2011 to the rainy season of 2013, in a total of four samplings. The zooplankton community was collected through vertical hauls with a 50 μm plankton net and immediately preserved in a 4% formalin solution. In the laboratory, the individuals were identified to the lowest possible taxonomic level, based on Koste (1978) and Elmoor-Loureiro (1997). For abundant species in each sample, three subsamples were counted in either a Sedgewick – Rafter cell under a microscope (for rotifers and nauplii) or in open chambers under a stereomicroscope (for cladocerans, copepodites, adult copepods). In each subsample at least 100 individuals were quantified. Additionally, the entire content of the samples was checked to identify species with low abundances. The phytoplankton community was collected directly in the lakes by immersing flasks of 100 mL below the surface of the water and immediately preserved in a Lugol's iodine solution. In the laboratory, the individuals were enumerated in random fields using the settling technique (Utermöhl, 1958). Individuals (cells, colonies and filaments) were counted, whenever possible, to reach 100 organisms of the most frequent species (Lund *et al.*, 1958).

2.3.1 Statistical analysis

Statistical analysis such as principal component analysis (PCA) was used to evaluate the similarity between lakes and the main factors controlling water quality in relation to the environmental factors such as temperature, TP, Chl-*a*, NH_4-N, NO_3, *Escherichia coli*, total coliform and cyanobacteria. This was carried out separately for rainy and dry seasons in all samples on raw data using the free statistical software R (R Core Team, 2012). The Non-Metric Multidimensional Scaling based on Bray Curtis (for abundance data) and Jaccard's (for presence and absence data) Dissimilarity Index, was used to display the phyto and zooplankton communities structure.

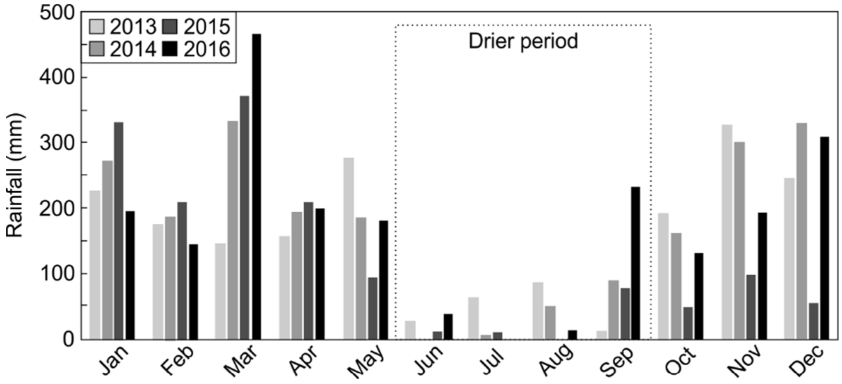

Fig. 2. Rainfall and temperature pattern in the study area for 2013–2016.

Table 1. Morphometric features of Carajás lakes according to the water frame work directive (WFD, Buraschi *et al.*, 2005).

Lakes	Altitude (m)	Classification	Mean depth (m)	Classification	Surface area (km^2)	Classification
Vl	723.3	Mid-altitude	7.42	Shallow	0.273	Very small
Am	700.5	Mid-altitude	5.2	Shallow	0.126	Very small
TI1	706	Mid-altitude	2.11	Very shallow	0.075	Very small
TI2	698	Mid-altitude	1.2	Very shallow	0.116	Very small
TI3	695.3	Mid-altitude	7.02	Shallow	0.252	Very small

Morphometric features (Buraschi *et al.*, 2005):
Altitude: high: >800 m; mid-altitude: 200–800 m; lowland: <200 m.
Depth (mean depth): very shallow: <3 m; shallow: 3–15 m; deep: >15 m.
Size (surface area): very small: 0–1 km^2; small: 1–10 km^2; very large: >100 km^2.

3 Results

3.1 Hydro-climatic variables

The monthly rainfall between 2013 and 2016 (Fig. 2) indicates a drier period from June to September with a total rainfall varying from 100 to 248 mm. The wetter period extends from October to May with a total rainfall from 1415 to 1970 mm. Regarding total annual rainfall, 2014 and 2015 were the wettest (2118 mm) and driest (1515 mm) years, respectively. The minimum and maximum air temperature registered from 2013 to 2016 were 17 and 35 °C, respectively.

3.2 Morphometry

According to the EU Water Frame Work Directive (WFD) adopted in 2000, the morphometric parameters used in the classification of lakes may be related to altitude, mean depth and surface area (Tab. 1). Based on this, the studied lakes of Carajás (located between 695 and 723 m amsl) fall into mid-altitude category (Tab. 1). The surface area of lakes varies between 0.075 and 0.27 km^2, which classified them into very small type. According to the morphometric classification of lakes imposed by the WFD (Buraschi *et al.*, 2005), the depth of the lakes was considered as shallow for Vl (7.4 m), Am (5.2 m) and TI3 (7.02 m), and very shallow for TI1 and TI2 (Tab. 1), since their mean depth values were within the range from 3 to 15 m and <3 m, respectively.

3.3 Limnological variables and classification

The range and average concentrations of various limnological parameters within seasonal changes are as shown in Table 2. The vertical temperature profile and some selective parameters based on their epi- and hypolimnetic measurements in the studied lakes are presented in Figures 3 and 4, respectively. The average water temperature shows little variation between the dry (25.73–30.1 °C) and rainy season (26.5–29.75 °C) and comparatively higher temperature was noted for TI1, and TI2. The vertical temperature profile (Fig. 3) shows moderate decrease towards bottom in both rainy and dry periods for Vl, and a slight decrease in the rainy season for Am and TI3 lakes. TI1 showed decrease of temperature at bottom, but this is not the case for TI2, although both lakes are shallow (~2 m, mean depth). The temperature difference between the surface and bottom water of Vl varied from 0.57 to 2.8 °C, while in Am, TI1, TI2 and TI3 varied from 0.03 to 2 °C (Fig. 3). According to the classification based on lakes stratification and mixing characteristics (Hutchinson and Löffler, 1956; Häkanson and Jansson, 1983), most of the studied lakes can be classified as polymictic lakes. DO concentrations in the lakes fluctuated from 6.1 to 13.3 mg/L in the rainy period and 5.2–10.5 mg/L in the dry period; higher concentrations were found in TI2 lake. Along the depth profile, DO concentration slowly decreases towards the bottom and in some cases the concentration was uniform. Although, DO content was higher at the surface than bottom (Fig. 4), the percentage of DO saturation remained at 80–140% throughout the entire water

Table 2. Summary of physico-chemical and microbiological variables (mean and range) measured in five lakes.

		TI1			TI2			TI3			Vl			Am		
		Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Rainy																
Temperature	°C	26.8	29.2	28.37	27.5	29.75	28.58	26.54	28.86	27.55	27.00	29.00	26.81	26.50	28.60	27.82
pH	–	4.80	5.60	5.38	5.29	5.70	5.50	3.60	5.48	4.99	4.39	7.28	5.90	4.02	6.71	5.27
EC	μS/cm	4.00	16.00	8.13	13.00	15.00	14.00	5.00	26.00	12.33	4.00	67.00	12.29	4.00	51.00	13.80
TDS	mg/L	3.00	10.00	5.13	6.00	8.00	7.00	3.00	15.00	7.22	3.00	40.00	8.42	3.00	25.00	8.51
Turbidity	NTU	3.20	9.20	5.60	3.40	7.50	5.45	0.40	3.40	1.94	1.66	4.50	2.92	0.40	2.23	1.37
NO_3	mg/L	<2.2	<2.2	–	<2.2	<2.2	–	<2.2	3.10	2.38	<0.2	9.39	0.55	<0.2	2.64	0.41
NH_4-N	mg/L	<0.1	<0.1	–	0.11	0.12	0.11	<0.1	0.22	0.11	<0.02	0.09	0.04	<0.02	0.13	0.06
TP	μg/L	<10	30.00	14.29	<10	30.00	20.00	<10	40.00	12.94	<10	150.00	35.83	<10	10.00	10.00
DO	mg/L	6.50	11.70	8.25	8.20	12.30	10.25	6.10	8.60	7.46	6.26	12.30	8.62	6.80	13.30	7.87
BOD	mg/L	<3	9.00	4.78	<3	10.90	6.95	<3	6.30	3.36	<3	<3	–	<3	<3	–
COD	mg/L	12.50	32.40	25.30	17.30	25.00	21.15	<5	20.00	12.14	<5	10.30	7.30	<5	15.00	8.53
Coliform_{tot}	NMP/100mL	22.00	914.00	322.88	79.00	457.00	268.00	<1	961.00	273.50	<1	172.00	40.03	7.00	961.00	98.58
Coliform_{thr}	NMP/100mL	1	19	5.5	<3	<3	–	<1	140	25	1	10	4	2	45	14
TOC	mg/L	6.60	12.00	8.45	4.50	7.60	6.05	2.10	5.60	3.37	<2	5.10	2.99	2.10	3.90	2.60
Cyanob	cell/mL	<3	603.00	166.75	<3	211.00	107.00	35.00	1980.00	641.56	<3	7821.00	3383.36	<3	140.00	35.52
Chl-a	μg/L	<3	9.00	4.63	<3	7.00	5.00	<3	4.00	3.06	0.01	38.00	6.92	<0.01	5.00	0.69
Z_{Secchi}	m	1.00	1.80	1.38	1.00	1.00	1.00	2.50	2.50	2.50	1.00	2.50	1.74	3.50	4.50	3.99
SO_4	mg/L	<2	<2	–	<2	<2	–	6.8	6.8	6.8	2.12	2.15	2.13	1.17	1.17	1.17
Al_d	mg/L	0.003	0.035	0.017	0.054	0.067	0.06	0.007	0.017	0.011	0.008	0.19	0.064	0.016	0.07	0.036
Fe_{tot}	mg/L	0.68	1.17	0.87	0.46	0.56	0.51	0.04	0.29	0.11	0.19	1.2	0.44	0.114	0.49	0.29
Fe_d	mg/L	0.21	0.56	0.33	0.11	0.18	0.15	0.001	0.179	0.05	0.026	0.88	0.202	0.053	0.47	0.209
Mn_{tot}	mg/L	0.006	0.011	0.008	0.007	0.007	0.007	0.006	0.117	0.009	0.008	0.01	0.009	0.009	0.013	0.01
Zn_{tot}	mg/L	0.004	0.321	0.058	0.002	0.07	0.041	0.003	0.14	0.032	0.006	0.39	0.068	0.006	0.36	0.054
Dry																
Temperature	°C	26.40	30.10	28.49	28.54	29.70	29.37	25.69	28.14	26.7	25.73	29.87	27.36	26.50	28.80	27.67
pH		4.99	6.27	5.46	4.80	5.24	5.02	3.98	5.55	4.83	4.01	7.13	5.39	4.13	6.46	5.12
EC	μS/cm	2.00	12.00	6.38	2.00	27.00	14.50	2.00	16.00	7.50	3.00	9.00	5.88	3.00	16.00	8.02
TDS	mg/L	2.00	9.00	4.38	2.00	15.00	8.50	2.00	8.00	4.22	2.00	6.00	4.12	2.10	11.20	5.61
Turbidity	NTU	5.10	7.30	6.21	2.60	6.90	4.75	0.50	19.50	3.41	0.20	3.92	2.47	0.10	2.12	0.94
NO_3	mg/L	<2.2	<2.2	–	<2.2	<2.2	–	<2.2	<2.2	–	<0.2	0.32	0.21	<0.02	0.35	0.13
NH_4-N	mg/L	<0.1	<0.1	–	0.17	0.20	0.18	<0.1	<0.1	–	<0.1	0.10	0.09	<0.02	0.15	0.06
TP	mg/L	<10	40.00	23.75	<10	10.00	10.00	<10	20.00	10.56	<10	40.00	13.53	<10	20.00	11.54
DO	mg/L	5.20	10.50	7.65	10.20	10.40	10.30	5.50	10.40	7.47	6.24	9.20	7.54	6.00	8.30	7.38
BOD	mg/L	3.00	8.10	5.73	<3	6.00	4.50	<3	27.40	4.39	<3	<3		<3	<3	–
COD	mg/L	23.20	34.70	28.79	14.00	21.10	17.55	<5	48.60	9.79	<5	47.00	16.71	<5	27.00	11.63
Coliform_{tot}	NMP/100mL	86.00	556	290.63	44.00	279	161.50	<1	134	29.89	<1	173	39.75	<1	624	45.96

Table2. (continued).

		TI1			TI2			TI3			Vl			Am		
		Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Coliform$_{thr}$	NMP/100mL	4	20	11	<1	20	–	<1	<10	–	<1	<10	–	7	<10	–
TOC	mg/L	6.10	10.00	8.21	2.50	5.20	3.85	1.60	13.20	3.30	2.10	5.00	3.14	1.20	3.10	2.43
Cyanob	cell/mL	<3	28300	7270	<3	3.00	3.00	1630	44200	14942	40	2808	1236	<3	177	21.60
Chl-*a*	µg/L	5.00	46.00	15.13	<3	8.00	5.50	<3	12.00	4.61	<0.01	<0.01	–	<1	2.72	1.17
Z_{Secchi}	m	0.80	1.00	0.90	0.50	1.40	0.95	1.95	2.50	2.27	1.70	2.10	1.90	2.40	4.50	3.78
SO_4	mg/L	<2	<2	–	<2	<2	–	<2	<2	–	<2	<2	–	2.33	<2	–
Al_d	mg/L	0.007	0.039	0.021	0.039	0.06	0.051	0.001	0.008	0.004	0.004	0.012	0.009	0.004	0.007	0.005
Fe_{tot}	mg/L	0.66	1.52	0.96	0.28	0.41	0.35	0.05	0.122	0.088	0.17	0.759	0.33	0.036	1.08	0.533
Fe_d	mg/L	0.012	0.637	0397	0.032	0.168	0.1	0.001	0.077	0.028	0.008	0.102	0.032	0.021	0.054	0.034
Mn_{tot}	mg/L	0.007	0.01	0.009	0.0147	0.0154	0.015	0.005	0.01	0.007	0.005	0.009	0.007	0.005	0.009	0.006
Zn_{tot}	mg/L	0.005	0.082	0.031	0.027	0.027	0.027	0.006	0.039	0.017	0.01	0.034	0.018	0.005	0.37	0.043

Min: minimum; Max: maximum; Avg: average;Coliform$_{tot}$: coliform total, Coliform$_{thr}$: coliform thermotolerant; Cyanob: cyanobacteria; Chl-*a*: chalorophyll-a; d: dissolved; tot: total. Values below the detection limit (DL) were reported as <DL and these values were replaced by DL values during the average calculation.

column; thus, a complete anoxia hypolimnion was not observed. Biological oxygen demand (BOD) is mostly ≤3 mg/L in all lakes, except a few exceptions.

The pH (3.6–7.2) was acidic to slightly alkaline in nature. Although the water pH was less varied between seasons, it was generally higher in the surface water and more acidic in nature towards the bottom (Fig. 4). According to Michigan Department of Environmental Quality (2013), the lakes were categorized as low to moderate pH and low alkalinity (as they have alkalinity <2 mg/L; Tab. 3), which indicates lesser buffering capacity and high degree of sensitivity to acid inputs (*e.g.* Taylor, 1984). EC was low in both periods, though higher values were recorded in the rainy period (avg, 8.1–14 µS/cm). In general, the EC is not correlated with depth (Fig. 4), but, except few outliers, higher values were observed in shallowest lake, TI2. This may likely be caused by the increase of dissolved ions at the benthic zone due to more intense chemical activity. The EC values have a strong relation with TDS. Turbidity had low variation between seasonal periods, as well as along the vertical profile, but it was highly variable among lakes (Fig. 4). Higher values in TI1 and TI2 indicate that the presence of organic and inorganic suspended materials is favored in shallow lakes as they are more susceptible to wind action and high organic decomposition. Among the nutrient concentration in lakes, TP varied from <10–150 µg/L to <10–40 µg/L in the rainy and dry periods, respectively. Highest TP was found in Vl, but no conclusive seasonal and vertical trend was observed (Fig. 4). The total N, nitrate (NO_3) and ammonia (NH_4-N) were low in all lakes, but a little higher values were observed in Vl lake. Total N concentration varied from 0.32 to 0.54 mg/L and the level of potential risk of eutrophication based on TN concentration is low to medium (Vollenweider, 1976; Cardoso *et al.*, 2001). Total organic carbon (TOC) concentration was comparatively higher in the rainy season than in the dry season. The vertical distribution of TOC was relatively homogenous in all lakes, with highest concentration was in Tl1. Water hardness is attributed to presence of alkaline earth metals mainly Mg and Ca in solution. On the basis of total hardness (<5 mg/L in all lakes), lake waters can be categorized as soft water (Tab. 3) following the guideline of Michigan Department of Environmental Quality (2013).

Heavy metals are another class of pollutants responsible for several heath diseases. This study analyzed the concentrations of Al, Ag, Ba, B, Be, Cd, Cr, Co, V, U, Pb, Cu, Fe, Mn, Ni, Si, Se, Hg, and Zn in the collected water samples, where only Fe, Al, Mn, and Zn were detected, while other were below detection limit, thus they are not presented in Table 2. The concentrations of Fe(t) and Fe(d) showed mixed patterns with respect to seasons, but varied between lakes, highest concentrations were measured for Tl1. Along the profile, Fe (t) concentrations were comparatively lower at the surface than bottom.

The water transparency (Z_{Secchi}) varied widely between lakes. It was lowest for TI2 and highest was for Am (Tab. 2). Comparing different seasons, Z_{Secchi} was lower during the dry period. Chl-*a* concentrations ranged from <1 to 38 µg/L in the rainy period and from <1 to 46 µg/L in the dry period. The highest values in both periods were observed at Vl and Tl1, whereas Tl2 and Am have presented the lowest values (Tab. 2). Cyanobacteria was also higher in the dry period and varied from <3 to 44200 cell/mL while in the rainy period varied

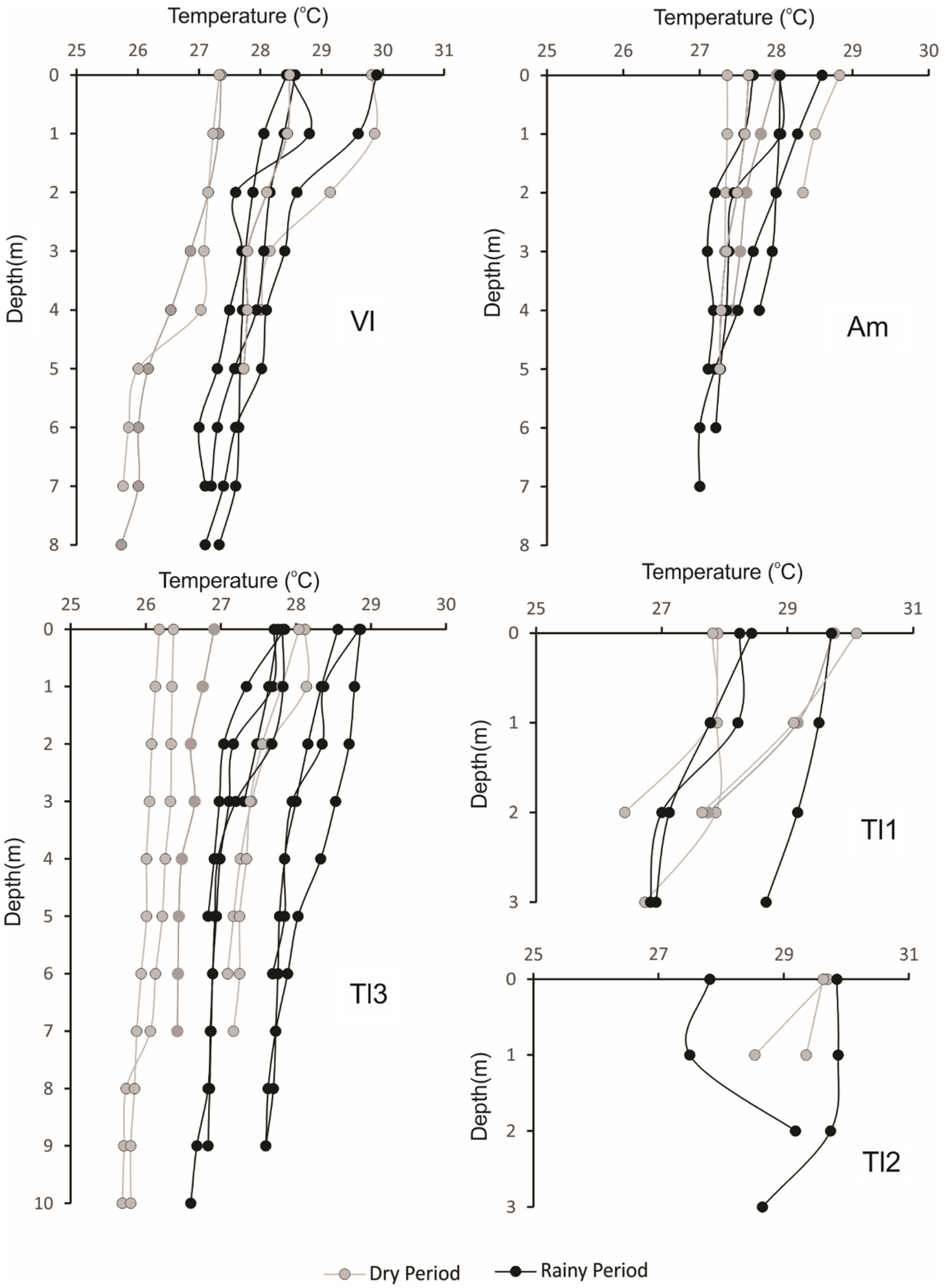

Fig. 3. Vertical temperature profile in all lakes during the dry and rainy seasons.

from <3 to 7821 cel/mL; lower concentrations were recorded for TI2 and Am in both periods. Both Chl-a and cyanobacteria show weak distribution pattern along the vertical profile (Fig. 4).

Table 4 presents the CONAMA classification of various parameters based on average concentrations in the studied lakes. This indicates the concentrations of DO, turbidity, and Chl-*a*, except for TI1 Lake, and cyanobacteria conform to Class I and II in both periods. Concentrations of Cl^-, NO_3^{-1}, NO_2^-, SO_4^{2-} dissolved Al, dissolved Fe, total Mn and total Zn conform to Classes I and II in both periods, except for TI1 Lake, where dissolved Fe concentration may conform to Class III. Regarding the *E. coli* (coliform thermotolerant) content (Tab. 4), Carajás lakes are classified as Class I according to CONAMA Resolution 357 (Brasil, 2005). Furthermore, the number of faecal coliform or *E. coli* in Carajás lakes did not exceed 10 NMP/100 mL and based on this most of the waters of the Carajás lakes are considered as suitable for swimming and fishing according to EPA (2009), but not for drinking purpose as it shows low to intermediate risk following WHO (1997).

The WQI values are ranging from 74 to 80 (TI1), 72 to 78 (TI2), 67 to 81 (TI3), 71 to 92 (Vl) and 71 to 86 (Am) in the rainy season and 73 to 78 (TI1), 73 to 75 (TI2), 68 to 82 (TI3),

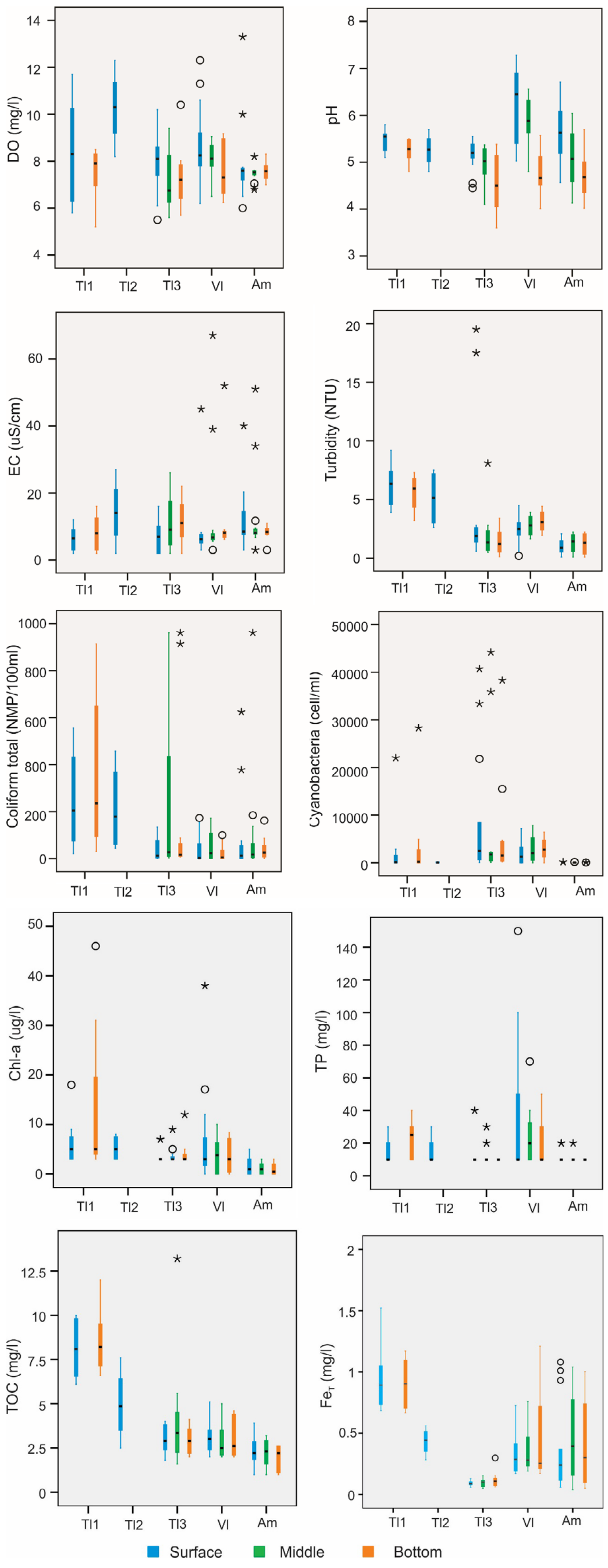

Fig. 4. Box plot showing the vertical distribution (surface, middle, bottom) of water quality parameters in the studied 5 lakes.

71 to 92 (Vl) and 66 to 90 (Am) in the dry period (Fig. 5). This indicates most water samples were classified as good to excellent quality in both periods. The TSI of all lakes in both dry and rainy season are presented in Figure 6. Vl, TI1 and TI2 showed a broad range of trophic conditions and can be classified as oligotrophic to eutrophic. TI3 was classified into oligotrophic state and Am was classified as ultra-oligotrophic to slightly oligotrophic. TI1 and TI2 show higher trophic state during the dry period, while Vl shows higher trophic state during the rainy season.

PCA results of water quality parameters for both periods have been given in Figure 7, which shows factor loading of principal components (eigenvector > 1) along with their cumulative variance (%). This extracted three principal components which accounted for the majority of the variance. The first two main factors of PCA showed significant associations of different variants. In rainy period (Fig. 7), the first component (PC1) explained 33% and PC2 represented 21.7% of the total variance. Both PC1 and PC2 shows high positive loading of Chl-*a*, TP and cyanobacteria, while total coliform, *E. coli*, NO_3 and NH_4 and temperature were associated negatively with PC1 and positively with PC2, but only Secchi was associated negatively with both PC1 and PC2. This association clearly shared almost all lakes, except lake Am. Also, in this season the TI lakes tended to group together, and the Vl and Am became more prominent. In dry period (Fig. 7), PC1 and PC2 are accounted for 35.4% and 19.7% of the total variance, respectively, and only Secchi showed high positive loading in PC1. Cyanobacteria, Chl-*a*, NO_3 and NH_4 were negatively loaded in both PC1 and PC2 while total coliform, temperature, TP and *E. coli* were positively loaded in PC2. This also indicates some similarity between all lakes other than Am. In this period, part of the samples of the Am were grouped with the Vl and TI3 but this was not so prominent in the rainy season.

3.4 Plankton community

A total of 51 zooplankton and 102 phytoplankton taxa were collected during the period of sampling. For the zooplankton community, rotifers were the richest group with 28 taxa, followed by cladocerans (17 taxa) and copepods (6 taxa) (Tab. S1). The genus *Polyarthra*, *Diaphanosoma* and *Notodiaptomus* were the most abundant and frequent all over the study. For the phytoplankton community, the groups Zygnemaphyceae, Cyanophyceae and Chlorophyceae were the richest ones with 28, 24, and 22 taxa, respectively (Tab. S1). Regarding species richness, zooplankton was highest in Vl, whereas phytoplankton was highest in TI1. In general, the species richness for both group of organisms was higher mainly in the dry season (Fig. 8). For the zooplankton, the highest species richness was observed in Vl (23 species, Fig. 8) while in the phytoplankton community the highest richness was recorded in the TI1 (35 taxa, Fig. 8C). The highest densities were observed in the rainy season for both zooplankton and phytoplankton communities (Fig. 8). The highest total density for phytoplankton was 4.3 × 10^5 individuals/m^3 in TI1 and for zooplankton was 4.7 × 10^5 individuals/m^3 also in TI1 (Figs. 8D and 8B, respectively). The environments from Serra dos Carajás showed some peculiarities in their zooplankton and phytoplankton community composition

Table 3. Level of pH, alkalinity, and hardness in water collected from Carajás upland lakes and their classification.

Lakes	pH		Alkalinity		Hardness	
	Range	Categories*	Concentrations (mg/L)	Acid-rain sensitivity***	Concentrations mg/L $CaCO_3$	Class**
Vl	4–7.3	Low-moderate	<2 (low)	high	<5	soft
Am	4–6.7	Low-moderate	<2 (low)	high	<5	soft
TI1	4.8–6.2	Low	<2 (low)	high	<5	soft
TI2	4.8–5.7	Low	<2 (low)	high	<5	soft
TI3	3.6–5.55	Low	<5 (low)	high	<5	soft

* pH: low (<6.5); moderate (6.5–9); high (>9); total alkalinity (mg/L as $CaCO_3$): low (<23); moderate (23–148); high (>148) (Michigan Department of Environmental Quality, 2013).

** Levels of hardness (mg/L $CaCO_3$): soft (0–60); moderate (61–120); hard (121–180); very hard (>180) (Michigan Department of Environmental Quality, 2013).

*** Sensitivity of lakes acid rain (Taylor, 1984) based on alkalinity (mg/l as $CaCO_3$): high (0–2); moderate (2–10); low (10–25); nonsensitivity (>25).

(Fig. 9). The zooplankton from TI2 and TI3 tended to be more similar between them, compounding a group separated of the others lakes, independent of the season and the type of data (abundance or presence/absence) (Fig. 9A and C).

4 Discussion

4.1 Water quality assessment

In accordance with the physical, chemical and microbiological characteristics of water obtained during the studied period, it was confirmed that lake waters from the Carajás region are of good quality and the average concentrations of most of the parameters, except few exceptions, were within the limit of class I and II freshwaters proposed in Brazilian environmental law (Brasil, 2005), and this assessment was less varied between seasonal climatic periods.

4.2 Limnological characteristics and their controlling factors

The decrease of Secchi depth (water transparency) in the dry period is mainly due to reduction of water depth. However, variation of Secchi depth between lakes is likely caused by various factors such as phytoplankton biomass, morphological features of lakes, catchment soil erosion and internal lake processes such as resuspension and diffusion (Hakanson, 2005). Phytoplankton biomass has an inverse relationship with water transparency (Chellappa *et al.*, 2009b; Cunha and Calijuri, 2011), and this relationship was clearly established in Am lake, where higher Secchi is related to lower phytoplankton biomass. On the other hand, lower Secchi depth in TI1 and TI2 is highly influenced by the morphological features of lakes, mainly shallower depth. This may be the cause for high TOC and turbidity in TI2 and TI1, as the shallow depth leads to more decomposition of organic matters in sediments and thereby increase of suspended particles at the benthic zone. Therefore, morphometric factors are important for identifying water body types related to water quality (Moses *et al.*, 2011; Stefanidis and Papastergiadou, 2012).

Water temperature slightly differed between rainy and dry seasons, but comparatively higher temperature in TI1 and TI2 could be attributed to the very shallow bottom exposed to direct sunlight. Furthermore, though water temperature varied between surface and bottom of the lake, the maximum difference was ≤2 °C (with few exceptions). This indicates that these lakes were weakly stratified in both seasons and, in some cases, they are relatively homogenous and a thermocline is indistinct. This is mainly influenced by morphometric characteristics, mainly shallow depth which favored mixing processes by wind action, besides other factors such as air temperature, high precipitation, and convention mixing (Podsetchine and Schernewski, 1999; Sahoo *et al.*, 2016). Similar studies are reported from Kashmir valley lakes (Kaul, 1977).

In lentic freshwater ecosystems, patterns of thermal stratification play an important role in controlling the vertical distribution of nutrients and DO (Ezekiel *et al.*, 2015; Sahoo *et al.*, 2016). In this study, weak thermal stratification possibly caused vertical mixing (from surface to bottom zones) of DO and nutrients (mainly TP) in the water column and absence of anoxia hypolimnic zone in all lakes. Nevertheless, higher DO content in the surface layer is possibly due to more photosynthetic activities and/or the diffusion of atmospheric oxygen by wind action (Downing and Truesdale, 1995) and lower hypolimnetic oxygen could be due to decomposition of organic matter by aerobic bacteria in bottom sediments. Weak thermal structure of waters may also be the cause of vertical mixing of biological parameters such as Chl-a, cyanobacteria and coliform, as it controls the distribution of DO and TP in water columns. Although, sediments play an important role in sediment-water nutrient exchanges, low concentrations of TP in bottom water may have influenced by sediment organic matter, redox conditions, and various Fe-oxyhydroxide minerals, which potentially affected the strength of ionic phosphorus sorption to sediment surfaces (Wetzel, 2001).

The principal water bodies are found to be acidic and this can be explained by the absence of base and by the ferruginous lateritic nature of catchment. This may have caused lower alkalinity and lesser buffering capacity of water bodies. On the other hand, it leads to high degree of sensitivity to acid inputs (*e.g.* Taylor, 1984). More acidic pH towards bottom may be attributed to the higher bacterial decomposition of sedimentary organic carbon which releases CO_2 and H_2S that make the

Table 4. Lake water classification based on the average concentrations of water quality parameters provided in Table 1 in relations to CONAMA Resolution 357 (Brasil, 2005).

Parameters	Vl		Am		TI1		TI2		TI3		Resolução CONAMA 357/2005		
	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Class I	Class II	Class III
DO (mg/L)	I	I	I	I	I	I	I	I	I	I	>6	>5	>4
BOD (mg/L)	I	I	I	I	III	II	II	III	II	II	3	5	10
TP (μg/L)	I	III	I	I	II	I	I	I	I	I	20	30	50
Turbidity (NTU)	I	I	I	I	I	I	I	I	I	I	40	100	100
Cl^- (mg/L)	I, II	I, II	II	II	II	II	II	II	II	II	250	250	250
Fecal coliform *E. coli* (NMP/100ml)	I	I	I	I	I	I	I	I	I	I	200	1000	4000
NO_3^- (mg/L)	II	II	II	II	II	II	II	II	II	II	10	10	10
NO_2^- (mg/l)	II	II	II	II	II	II	II	II	II	II	1	1	1
SO_4^{2-} (mg/L)	II	II	II	II	II	II	II	II	II	II	250	250	250
Dissolved Al (mg/L)	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	0.1	0.1	0.2
Dissolved Fe (mg/L)	I,II	I,II	I,II	I,II	III	I,II	I,II	I,II	I,II	I,II	0.3	0.3	5
Total Mn (mg/L)	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	0.1	0.1	0.5
Total Zn (mg/L)	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	I,II	0.18	0.18	5
Chlorophyll-a (μg/L)	I	I	I	I	II	I	I	I	I	I	10	30	60
Cyanobacteria (cell/mL)	I	I	I	I	I	I	I	I	I	I	20.000	50.000	100.000

E. coli (*Escherichia coli*) is determined as coliform thermotolerant. Class I: These waters that can be designed to supply for consumption human (after simplified treatment); Class II designed to supply for human consumption (after treatment conventional); Class III: water that can be designed to supply for consumption human (after conventional or advanced treatment).

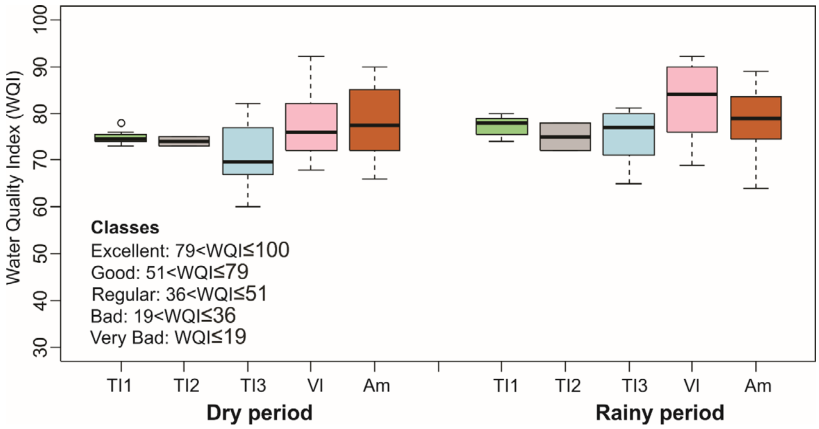

Fig. 5. Variation of Water Quality Index (WQI) in both periods of Violão, Amendoim, Três Irmãs lakes.

water acidic (Wetzel, 1983). Nevertheless, the higher values of pH at the surface associated with higher temperatures may be due to higher photosynthetic activity, which decreases CO_2 assimilation (Sahoo *et al.*, 2016). Decomposition of organic matter in sediments also leads to reduce Fe^{3+} to Fe^{2+}, which has strong ability to diffuse to overlying water. This may be caused high concentrations of Fe in bottom waters.

In most lake waters, the total concentrations of major cations such as Ca, Mg, Na, and K are equal to the sum of the concentrations of Cl^-, SO_4^{2-} and HCO_3^-. Exceptions to this are the studied water containing high concentrations of other cations, *e.g.* Fe. Low contents of Ca and Mg and high contents of Fe in lake waters may be explained by the dominance of Fe-rich laterite and absence of carbonate rocks in the catchment areas. This also caused very low total salt contents (*i.e.*, avg. EC < 15 μS/cm) and low alkalinity, as well as very low concentrations of heavy metals in waters. Therefore, there is a close correspondence between the rock substrate in the catchment and metal contents in water (*cf.* also Camarero *et al.*, 2009; Ramos *et al.*, 2016). Anions usually comprise more diverse sources than cations. The capture of atmospheric CO_2 during rock weathering provides bicarbonate, and atmospheric deposition brings Cl^- and SO_4^{2-}, although the main source of the latter is usually rock weathering (Camarero *et al.*, 2009). Low content of these ions in waters could also be due to geological control.

Although WQI indicates high similarity among the studied lakes regarding their water quality (good to excellent categories), the trophic state of these lakes varied substantially from ultra-oligotrophic to eutrophic states. This is in general controlled by nutrient contents mainly TN and TP (Cardoso *et al.*, 2001; Sahoo *et al.*, 2016), thus these concentrations were

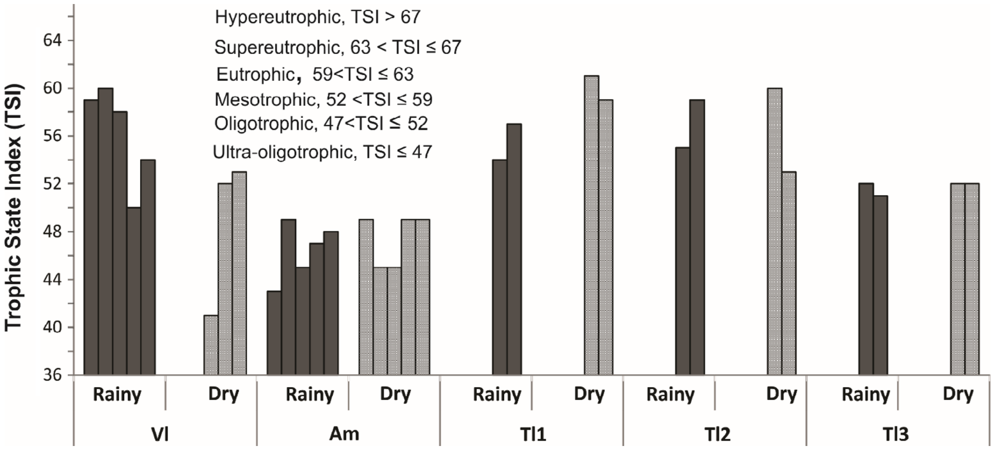

Fig. 6. Trophic state of studied lakes during both dry and rainy seasons. Each solid bar indicates one sampling period between 2013 and 2016. TSI is calculated based on the average concentrations of patameters in each sampling period.

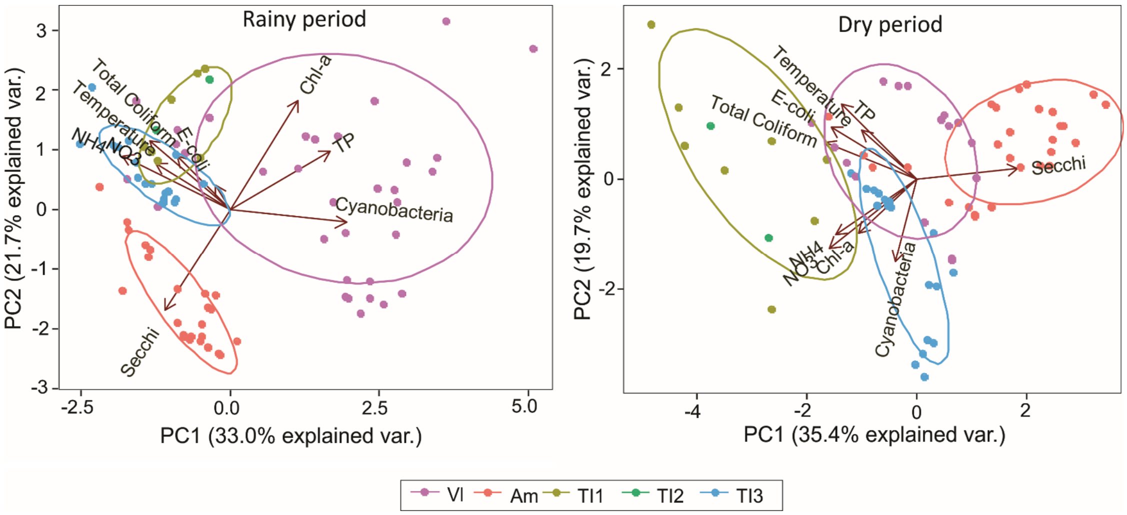

Fig. 7. Principal Component Analysis of limnological parameters studied during both dry and rainy seasons from all five lakes. Grouping of lakes was based on the environmental variables such as Temperature, TP, Chl-*a*, NO_3, NH_4, Coliform, Cyanobacteria and Z_{Secchi}.

used as a proxy to evaluate the potential risk to lake eutrophication. In the studied lakes, the TN concentrations indicating low to medium risk of eutrophication (Vollenweider, 1976; Cardoso *et al.*, 2001). Regarding, TP content, Vollenweider (1976) suggests a TP concentration of only 30 µg/L as the lower limit necessary to promote excessive algal growth and eutrophic conditions. Using this value as reference, the TP content in Vl and TI1 may promote algal growth and this may be the cause of higher trophic nature of these lakes. In addition, morphological feature, such as shallow depth which causes lower Secchi depth, is also a potential factor for high eutrophic conditions, this is observed in TI1 and TI2.

In the PCA analysis, Am lake shows different behavior when compared to Vl, TI1 and TI3, in both periods, due to low content of TP, Chl-*a* and cyanobacteria. This variability may be due to different catchment characteristics which control nutrients levels, as the latter lakes have locally mafic/Al-enriched soils in their catchment while the former lake presents mostly lateritic crust, which is less susceptible to chemical weathering. Furthermore, in the case of Vl lake, P-enrichment could be caused by the presence of guano in the caves and margins of the catchment through leaching or erosional transport. This is possibly the reason of the association of Chl-*a* with TP observed in rainy period. However, this explanation is not valid for the dry period as these variables are poorly correlated, indicating TP was probably not the only limiting factor for lake productivity. Similarly, the poor correlation between Chl-*a* and NO_3 and NH_4 also indicates that multiple factors control their abundance. Alcântara *et al.* (2011) discussed several environmental factors such as water level, surface temperature, turbidity and mixing process, which can influence the nutrient availability, can control the Chl-a concentrations. Light conditions could be an additional factor to this because increase of light conditions facilitate algal production, which subsequently increases Chl-*a* concentrations. This is possibly the reason of comparatively high Chl-*a* contents in TI lakes. Although many studies have shown that the increase in abundance of cyanobacteria can be attributed to nutrient enrichment, such as TP and TN (Chellappa *et al.*, 2009b; Wojciechowski and Padial, 2015), in this study these variables are poorly correlated. A recent study in Peri Lake (Santa Catarina

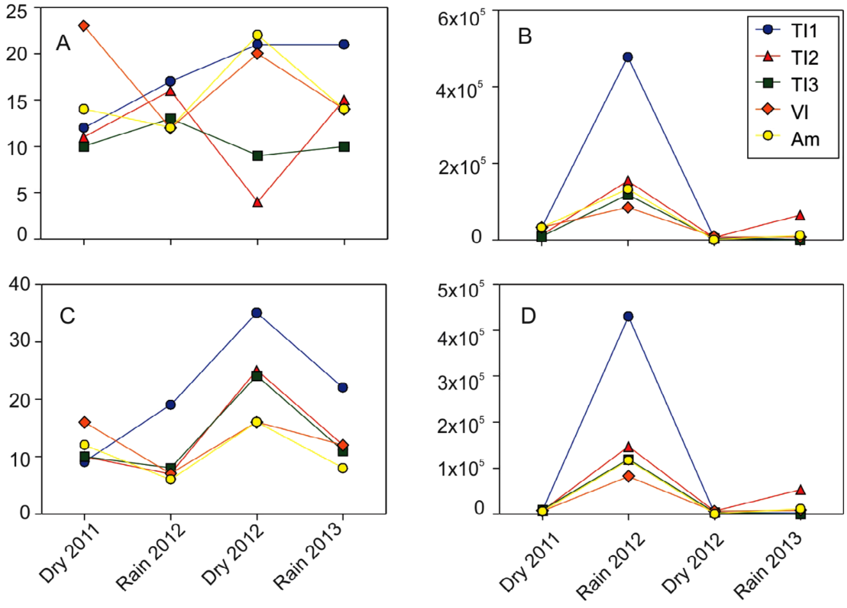

Fig. 8. Species richness and abundance of zooplankton (A and B) and phytoplankton (C and D) community in all the lakes between 2011 and 2013

Island, Brazil) has also reported that cyanobacteria can dominate even in low nutrient conditions for long periods (Tonetta *et al.*, 2015). This can be due to other factors such as light conditions and morphology of lakes (Dokulil and Teubner, 2000). Morphological features such as shallow depth are responsible for turbid water by basin flushing and frequent re-suspension of organic matter particles from the sediment, which influence the density of plankton population. This possibly acted as a stress factor to reduce the relative abundance of cyanobacteria in TI1 and TI2. Moreover, seasonal influence can be one of the important factors controlling this, as lower content of cyanobacteria in the rainy period, except few exceptions, can be explained by the instability or mixing of the water columns in this period, due to frequent rainfall events (Dantas *et al.*, 2008). This was also observed in previous studies conducted in eutrophic reservoirs in Brazil (Cunha and Calijuri, 2011; Dantas *et al.*, 2008; Costa *et al.*, 2009). Poor associations of *E. coli* and total coliform with TP and nitrogen compounds during both dry and rainy seasons indicate that these biological variables may have mixed influence in their abundance.

4.3 Plankton community and controlling factors

The plankton community is considered a good indicator of changes in aquatic environment because they include different groups with different life history traits, dispersal abilities and short reproductive processes, which allow them to have a rapid response (Cáceres and Soluk, 2002; Calijuri *et al.*, 2002; Frisch *et al.*, 2012; Silva *et al.*, 2013). In the present study, rotifers were the richest among the zooplankton community. This dominance of rotifers has also been observed in several studies in Brazilian lakes, wherein rotifers were more speciose than microcrustaceans (Robertson and Hardy, 1984; Bozelli, 1992; Rocha *et al.*, 1995; Neves *et al.*, 2003; Lopes *et al.*, 2014). Similarly, the genus *Polyarthra*, *Diaphanosoma* and *Notodiaptomus* which were most abundant and frequent in all over the study are typically recorded and dominant in amazon ecosystems (Bozelli, 1992; Previattelli *et al.*, 2013; Brito *et al.*, 2015).

Regarding phytoplankton community, the groups Zygnemaphyceae, Cyanophyceae and Chlorophyceae are frequent and abundant in the Amazon basin and they have been registered in several studies in the area (Huszar and Reynolds, 1997; Melo and Huszar, 2000; Souza and Melo, 2011; Cunha *et al.*, 2013). In the Carajás region the phytoplankton community was characterized by small chroococcales (*Synechocystis* spp. and *Synechococcus* spp.) with genus typical of clear and oligotrophic lakes; and chlorococcales (*Scenedesmus* spp.) and desmids (*Closterium* sp.; *Cosmarium* sp.) together with filamentous algae (*Lyngbya putealis*), more commonly observed in the dry seasons.

Plankton community varied widely among lakes. The highest richness phytoplankton community in the TI1 is probably due to the decrease of water level, which results in the concentration of nutrients and it triggers off increase in phytoplankton production and consequently zooplankton productivity (Melo and Huszar, 2000; Okogwu, 2010). Moreover, in the dry season, there is more concentration of individuals in the water column which increases the probability of sampling rare species. However, some species such as *Bosminopsis deitersi* (Cladoceran) were observed mostly in the rainy season. This fact can be associated to the enlargement of the habitat of this phase, which minimizes the interspecific competition (Hardy, 1980; Rocha *et al.*, 1995).

Seasonal and spatial influence is also evident on both zooplankton and phytoplankton communities, which were abundant in rainy seasons and in TI1 Lake. This antagonistic relation between species richness and abundance regarding the seasonality may be related to the dominance of some species in the rainy season because of the lack of food or decrease of

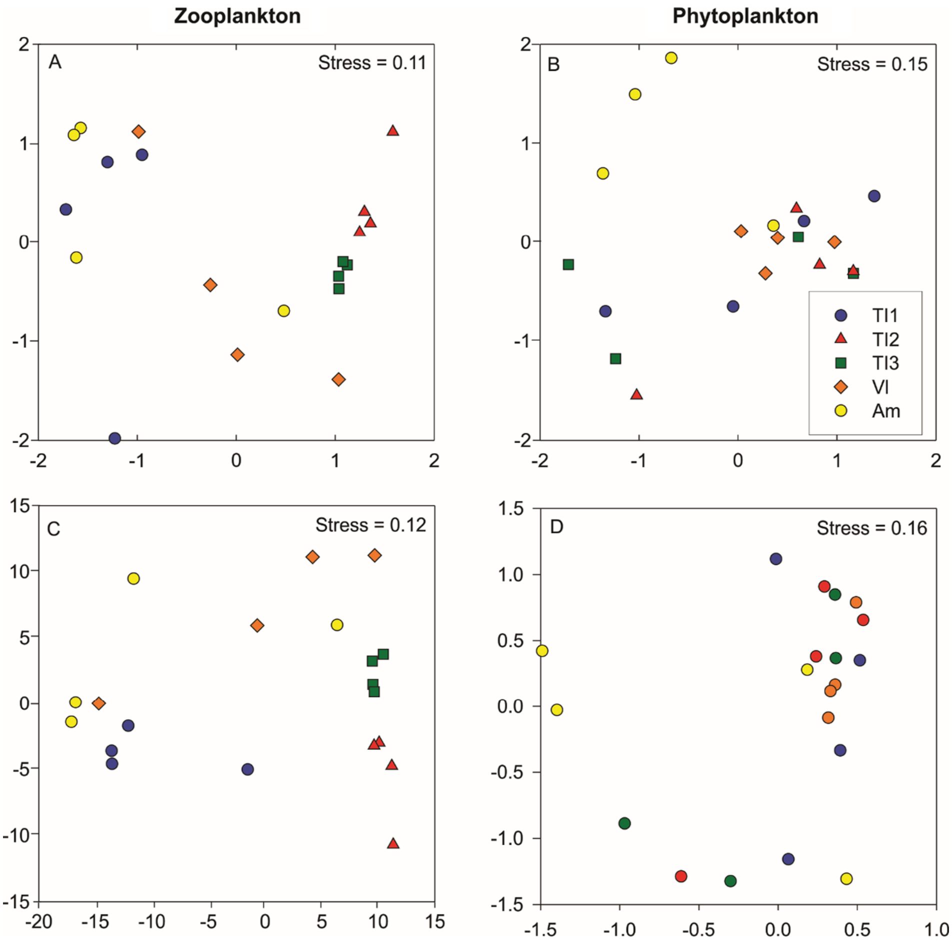

Fig. 9. NMS of the zooplankton and phytoplankton community of all the systems studied, for abundance (A and B) and presence and absence (C and D) data using a Bray-Curtis and Jaccard Index.

pressure of predation and competition. In fact, some species such as *Polyarthra dolichoptera* (rotifer) and *Synechocystis aquatilis* (Cyanophyceae) that occur throughout the studied lakes have peak abundances in the rainy season when compared to the dry season. These species are considered cosmopolitans and have tolerance to a wide environmental gradient (Domingos *et al.*, 1994; Melo and Huszar, 2000; Obertegger *et al.*, 2014), such as high DO values and low nutrients content, characteristics observed in our environments in the rainy season. Although high values of DO can favor the development of plankton community, the lack of food due the low nutrient content contributes to the species depression in this season. For some cyanobacterias, such as Synechocystis, which can grow rapidly (C-strategists) can become dominant in periods of high water since they are the morphological types which are better adapted to this kind of environment (Melo and Huszar, 2000). Besides that, cyanobacterias are in general considered an inadequate food for zooplankton which favors their growth (Arcifa *et al.*, 1994).

The lakes from Serra dos Carajás showed some peculiarities. The TI lakes use to be connected in the rainy season, and this can contribute for the higher similarity between them. In the other hand, the Vl, and TI1 also tend to be more similar, even without connection. The same pattern was observed for the phytoplankton community, wherein all the lakes have not showed a clear spatial distribution. This result may suggest that the distance among the different lakes may not have been sufficient to create dispersal barriers for these groups. Some authors suggest that single-celled organisms, such as algae, may have higher dispersal rates due to their small size, and spatial factors may have little influence on community structuring (Finlay *et al.*, 1996; Hillebrand *et al.*, 2001).

Moreover, the phyto and zooplankton, besides their small sizes, can produce dormant stages (cysts and resting eggs) capable to resist to several environmental conditions and are able to be transported by different vectors such a wind, water and animals, favoring the dispersal (Incagnone *et al.*, 2015). Some studies have shown that zooplankton organisms can effectively disperse in distances as high as 100 km (Shurin, 2000), suggesting the inexistence of real dispersal barriers (Cohen and Shurin, 2003; Havel and Shurin, 2004; Louette and De Meester, 2005; Vanschoenwinkel *et al.*, 2008). In this study, since the major distance among the lakes was not over 10 km, the absence of dispersal limitation among these groups can be considered.

5 Conclusions

The results obtained during this study indicated that the Carajás upland lakes are shallow and weakly stratified (classified as polymictic type), which controlled vertical mixing of limnological parameters and absence of anoxia hypolimnic zone in all lakes. Water quality was “good” and the parameters were mostly in compliance with class I and II of the Brazilian legislation (CONAMA Resolution n° 357/05). Seasonal variation of water quality was very small, except for biological parameters. High concentrations of total Fe and very low concentrations of other metal ions in water is due to the catchment lithology which mainly composed of ferruginous laterite. Trophic state index (TSI) varies significantly among the lakes, with lakes Am and TI3 are showing oligotrophic and higher TSI values are corresponding to Vl, TI1 and TI2. PCA results indicate that these lakes differ in their limnological parameters, with lower values of TP, Chl-*a* and cyanobacteria in Am lakes in contrast to other lakes; but TP is not solely controlling the phytoplankton biomass in these lakes. Nevertheless, limnological characteristics of lakes are highly influenced by lithological and morphological parameters. In general, the Carajás lakes were more oligotrophic compared to other lagoons in other regions of Brazil, presenting a small planktonic community and very similar between them, suggesting that physical distance was not an efficient dispersion barrier for them. This study outcome contributes to understand the common limnological processes in Amazonian upland lakes. In addition, this work can give valuable insight for developing a lake index system for the conservation and preservation of lakes in the Carajás area.

Supplementary Material

Supplementary tables.
The Supplementary Material is available at http://www.limnology-journal.org/10.1051/limn/2017026/olm.

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