Rainfall increases the biomass and drives the taxonomic and morpho-functional groups variability of phytoplankton in a subtropical urban lake

A pluviosidade aumenta a biomassa e impulsiona a variabilidade dos grupos taxonômicos e morfo-funcionais do fitoplâncton em um lago urbano subtropical

Matheus Vieira da Silva[1*] (ID) and Susicley Jati[2] (ID)

[1]Programa de Pós-graduação em Ecologia, Laboratório de Limnologia, Departamento de Ecologia, Instituto de Biologia, Universidade Federal do Rio de Janeiro – UFRJ, Av. Carlos Chagas Filho, 373, Cidade Universitária, CEP 21941-540, Rio de Janeiro, RJ, Brasil

[2]Núcleo de Pesquisas em Limnologia, Ictiologia e Aquicultura – NUPELIA, Laboratório de Ecologia do Fitoplâncton, Universidade Estadual de Maringá – UEM, Av. Colombo, 5790, Bloco H-90, CEP 87020-900, Maringá, PR, Brasil

*e-mail: matheusvieirabio@hotmail.com

Abstract: Aim: To explore the short-term effects of rainfall events on the biomass, density, and richness of the phytoplankton community during dry and rainy periods, as well as on the selection and response of Morphology-Based Functional Groups (MBFG). **Methods:** The phytoplankton community and abiotic environmental variables were sampled over a short period in a subtropical urban lake during the dry and rainy seasons (2018-2019). Generalized Linear Models (GLMs) were generated to analyze the relationship between phytoplankton biovolume, density, and richness with abiotic variables. The predictability of phytoplankton functional groups was assessed using Redundancy Analysis (RDA). **Results:** There was an increase in the density and biovolume of the phytoplankton community during the rainy period. Species richness decreased with increased rainfall. The lake exhibited a high dominance of Cyanobacteria (MBFG VIII), mainly represented by *Raphidiopsis raciborskii* (Woloszynska) Aguilera in both periods studied. **Conclusions:** We found evidence supporting the hypothesis that rainfall events increase the density and biovolume of phytoplankton. Morphology-based functional groups served as efficient indicators of the lake's environmental conditions.

Keywords: ammonium; cyanobacteria; meteorological factors; precipitation.

Resumo: Objetivo: Explorar os efeitos a curto prazo de eventos de chuva na biomassa, densidade e riqueza da comunidade fitoplanctônica durante os períodos seco e chuvoso, bem como na seleção e resposta de Grupos Funcionais Baseados na Morfologia (MBFG). **Métodos:** A comunidade fitoplanctônica e as variáveis ambientais abióticas foram amostradas em um curto período em um lago urbano subtropical durante as estações seca e chuvosa (2018-2019). Modelos Lineares Generalizados (GLMs) foram gerados para analisar a relação entre o biovolume, a densidade e a riqueza do fitoplâncton com as variáveis abióticas. A previsibilidade dos grupos funcionais de fitoplâncton foi avaliada usando Análise de Redundância (RDA). **Resultados:** Houve um aumento da densidade e do biovolume da comunidade fitoplanctônica no período chuvoso. A riqueza de espécies diminuiu com o aumento da

pluviosidade. O lago exibiu uma alta dominância de Cyanobacteria (MBFG VIII), principalmente representadas por *Raphidiopsis raciborskii* (Woloszynska) Aguilera nos dois períodos estudados.
Conclusões: Encontramos evidências que sustentam a hipótese de que eventos de chuva aumentam a densidade e o biovolume do fitoplâncton. Os grupos funcionais baseados na morfologia serviram como indicadores eficientes das condições ambientais do lago.

Palavras-chave: amônia; cyanobacteria; fatores meteorológicos; precipitação.

1. Introduction

Urban lakes are designated spaces with multiple purposes, serving as sources of potable water for public supply, flood regulators, recreational areas for the population, and elements of landscape beautification in urban centres (Almanza-Marroquín et al., 2016). Additionally, these environments offer other ecologically significant services, such as controlling the effects of urban heat islands, resulting in localized temperature reduction and improved relative air humidity, thereby contributing to enhancing the quality of life for the populace (Chen et al., 2020, Gao et al., 2019).

The anthropogenic pressure in the vicinity of these environments favours the water eutrophication process (Bhagowati & Ahamad, 2019). Eutrophication refers to the phenomenon of overproduction of primary producers, induced by an increased influx of nutrients, mainly nitrogen and phosphorus, from allochthonous sources (Le Moal et al., 2019). Eutrophication is regarded as a globally-reaching environmental impact, ranking among the most severe issues associated with the preservation of aquatic ecosystems. Among the primary impacts caused by eutrophication, reductions in dissolved oxygen levels and decreases in water transparency stand out (Moraes 2009, Viana et al., 2009). Additionally, numerous studies have revealed a significant correlation between eutrophication of freshwater bodies and greenhouse gas emissions (Li et al., 2021).

Furthermore, the increase in water temperature and the frequency of rainfall events emerge as important climatic variables for the structuring and increase of phytoplankton biomass (Elliott, 2010; Weisse et al., 2016). This occurs because during periods of higher rainfall, there is an intensification in the input of allochthonous nutrients from the entire watershed, causing environmental enrichment (Richardson et al., 2019). Moreover, the increase in water temperature accelerates the reproduction rate of phytoplankton. The combination of these two factors can amplify phytoplankton blooms in subtropical environments, especially in the summer (Huisman et al., 2018; Zhou et al., 2020). However, this problem worsens when these blooms are formed by Cyanobacteria species. It is widely agreed in the scientific literature that the increase in water temperature promotes excessive proliferation and the formation of Cyanobacteria blooms (Weber et al., 2020, Zahra et al., 2020). This is because Cyanobacteria have a competitive advantage over other phytoplankton groups in warmer environmental conditions, since bloom-forming species of this group can reach their maximum reproduction rate at higher temperatures (Butterwick et al., 2005). The increase in cyanobacterial abundance can severely hinder the ability to control blooms and manage aquatic bodies. The excessive proliferation of cyanobacteria poses a significant threat to freshwater quality and global water security (Richardson et al., 2019).

In recent decades, algal and cyanobacterial blooms have become increasingly common around the world, especially in urban lakes (Zhang et al. 2021). Increased nutrient concentrations in these environments promote the intense growth of phytoplankton primary producers (*blooms*), especially algae and cyanobacteria, which can lead to considerable management challenges (Aubriot, 2019; Li et al., 2020; Søndergaard et al., 2017). These blooms compromise the multiple uses and ecosystem services of these environments, preventing activities such as public water supply, irrigation, animal watering, fish farming and laser activities (Fabrin et al., 2020, Veerman et al., 2022, Yang et al., 2020). This is because the species of cyanobacteria that form blooms are potentially producers of toxins (cyanotoxins), which can be bioaccumulated in the trophic chain, causing poisoning and even death of animals and people (Somdee et al., 2013, Veerman et al., 2022). When the high biomass of algae and cyanobacteria produced during bloom enters senescence, it can cause a deficit of dissolved oxygen, which is consumed during the decomposition process, further reducing water quality (Boyd, 2021; Maruya et al., 2023).

Phytoplankton plays essential roles in the functioning of aquatic ecosystems, contributing to carbon fixation and nutrient cycling (Tundisi & Tundisi, 2012; Willén, 2000). Moreover, due to

their composition of small-sized species and short generation cycles, these organisms serve as excellent environmental indicators (Silva et al., 2022), responding effectively to environmental changes, with noticeable fluctuations in community structure (Reynolds, 2006). In this context, the investigation of temporal variation in this community assumes crucial importance for understanding the dynamics of aquatic ecosystems, given that its oscillations can hold predictive value for potential alterations in environmental conditions (Huszar et al., 2000).

The polyphyletic origin and with a large number of species, the phytoplankton community exhibits high diversity of forms and sizes, which confers low predictive capacity when using only the traditional taxonomic approach (Kruk et al., 2021; B.Béres et al., 2024; Stela et al., 2024). The approach based on functional traits allows for broader generalizations than a phylogeny-based approach. Thus, employing the Morphology-Based Functional Groups (MBFG) approach can facilitate understanding of the ecology and environmental factors acting on phytoplankton (Kruk et al., 2010). In this approach, nine morphological traits were used to form the eight MBFGs: volume, surface area, maximum linear dimension, surface-to-volume ratio, presence of mucilage, flagella, aerotopes, heterocysts, and silica demand. In the morphology-based functional approach, functional traits are the fundamental units selected through environmental filters. Therefore, a similar environmental response is expected from species composing the same functional group in the face of a specific environmental filter (Bortolini & Bueno, 2017; Violle et al., 2007).

Although it is acknowledged that rainfall substantially influences the occurrence of phytoplankton blooms in urban lakes, a complete understanding of how these precipitation events alter lake conditions and consequently impact the phytoplankton community during different seasonal periods is not fully grasped. Furthermore, the comprehension of this community's dynamics during short sampling periods in subtropical climates is still in its early stages. Given these gaps, the present study aimed to investigate variations in phytoplankton community attributes (species richness, density, and biovolume) in the Lake of Ingá Park, during a short sampling period, and their relationships with environmental variables.

To accomplish this, we assume the following hypotheses: i) The classification of the phytoplankton community into morphologically-based functional groups will serve as efficient indicators of the lake's environmental conditions; ii) During the rainy season, it is expected that biovolume and density values will be higher compared to the dry season, due to nutrient inputs from runoff during the rainy period. Studying temporal fluctuations can provide insights for management strategies aimed at revitalizing the lake, ensuring water quality, and maintaining the balance of trophic chains within the ecosystem in question.

2. Material and Methods

2.1. Study area

The Municipality of Maringá is situated in the northwest region of the State of Paraná, Brazil (23°25'S and 51°25'W), presenting an average annual precipitation between 1,500 and 1,600 mm and average annual temperatures between 20°C and 25°C (Santos, 2003). The Ingá Park encompasses an area of 47.3 hectares and stands as one of the last remnants of the Atlantic Forest in the region, serving as the primary recreational environment for the population (Bovo & Amorim, 2009). It is covered by pristine forest, located within the phytogeological region of the seasonal semideciduous forest (Maack, 1981). The main lake within Ingá Park occupies approximately 1/5 of the total park area (Vaz et al., 1998) (Figure 1).

Currently, the lake's volume is largely maintained through rainwater drainage systems, as most of the natural springs that existed within the park, such as the emergence of the water table, have dried up due to slope impermeabilization and increased groundwater extraction in the vicinity of the park. As a result, there is no water renewal for the lake. Its water volume is greatly reduced during the dry period and replenished during the rainy season, with very rare episodes of water overflow through the gate of the dam, which is of the free weir type (Jati, 2019).

2.2. Sampling and analysis

Sampling of total phytoplankton and environmental abiotic variables was carried out during the dry season between May and June 2018 and during the rainy season between January and February 2019. Ten days of collection were established for each period, with a three-day interval between each collection. Depth samplings followed a gradient of light availability, with collections in the subsurface, at the boundary of the euphotic zone (Euphotic), and in the hypolimnion (Bottom), totalling 60 samples.
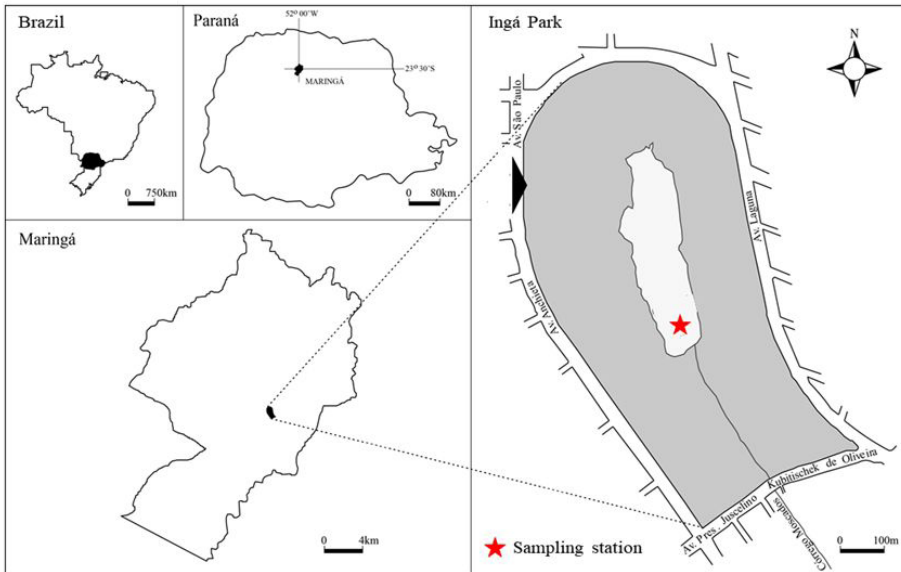
Figure 1. Location map of Ingá Park lake, Maringá, Paraná, Brazil.

Abiotic variables such as water temperature (Temp, °C), pH, maximum depth (Zmax, m), euphotic zone (Zeu, m) calculated as 2.7 times the Secchi disk depth (Cole, 1994), electrical conductivity (Cond, μS.cm-1), and dissolved oxygen (DO, mg L^{-1}) were collected in situ using portable digital potentiometers. Water turbidity (Turb, NTU) was measured with a turbidity meter. Concentrations of phosphate and total phosphorus (μg. L^{-1}; Golterman et al., 1978), nitrate ion, ammonium ion, and total nitrogen (μg L^{-1}; Mackereth et al., 1978) were estimated. Precipitation data for the study period were obtained from the meteorological station of the State University of Maringá.

Samples for phytoplankton analysis were collected in the subsurface of the lake's limnetic zone, directly into 100 ml bottles, and fixed in situ with an acetic lugol solution. For depth collections, a Van Dorn bottle was used. Phytoplankton density was estimated using an inverted microscope, following the Utermöhl method (Utermöhl, 1958). Sedimentation time was defined based on the sedimented volume in each sample (Margalef, 1983), and the counting of individuals (cells, colonies, and filaments) was done randomly, according to Lund et al. (1958). Density calculation was performed according to APHA (1995).

The phytoplankton biovolume was estimated by multiplying the density by the cellular volume of each organism, which was calculated based on geometric shapes according to Sun & Liu (2003). Species richness was considered as the total number of taxa recorded in each sample. Organisms were identified to the lowest taxonomic level using specialized literature. Phytoplankton organisms were grouped according to the eight Morphological Functional Groups (MBFGs) described by Kruk et al. (2010) and Reynolds et al. (2014), for a better understanding of the average size of organisms and their other morphological characteristics: MBFG I: includes small organisms with high surface-volume ratio (S:V); MBFG II: includes small flagellated organisms with silicified exoskeletal structures; MBFG III: includes large filamentous organisms with aerotopes; MBFG IV: includes medium-sized organisms without specialized characteristics; MBFG V: includes medium to large-sized unicellular flagellates; MBFG VI: includes non-flagellated organisms with silicified exoskeletons; MBFG VII: includes large mucilaginous colonies; MBFG VIII: includes nitrogen-fixing cyanobacteria (Figure 2).

2.3. Data analysis

Principal Component Analysis (PCA; Legendre & Legendre 1998) was employed to summarize environmental variability during each study period (dry and rainy) and across all lake compartments (surface, euphotic zone boundary, and bottom in the PCA, all available environmental variables were utilized, namely: water temperature, dissolved oxygen, pH, Secchi depth, nitrate (NH_3-N), ammonium (NH_4-N), phosphate (PO_4-P), and maximum depth.

The relationship between phytoplankton biovolume, density, and richness over time and with
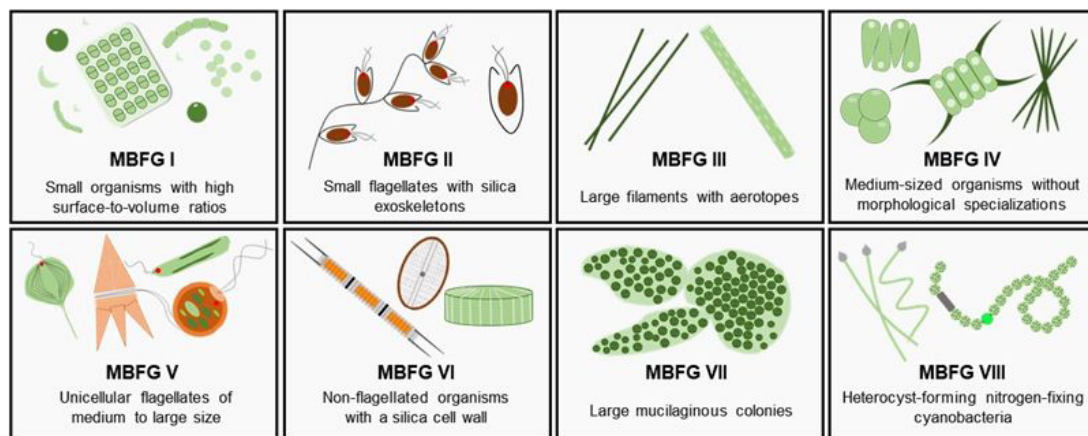
Figure 2. Schematic representation of the eight MBFGs, including a brief description of their morphology. S/V – Surface/Volume ratio. (Kruk et al., 2010; Reynolds et al., 2014).

predictor abiotic variables was presented through Generalized Linear Models (GLMs), incorporating Poisson error correction and a logarithmic link function. The latter employs maximum likelihood to calibrate model parameters (Austin, 1999; Mittelbach et al., 2001).

The predictability of phytoplankton functional groups (MBFG) was assessed using Redundancy Analysis (RDA), where functional group biovolume served as the response variable and environmental filters were employed as explanatory variables. The biological matrix underwent a Hellinger transformation due to RDA's linear nature, which also mitigates the impact of double zeros in similarity calculations between sites (Boccard et al., 2011). Co-linearity between environmental variables was identified using variance inflation factors (VIF), and the redundant environmental variables with VIF > 10 were removed before analysis. The VIF-selected explanatory variables were nitrate (NO3-N), ammonium (NH4-N), total phosphorus, water temperature, maximum depth, pH, dissolved oxygen, and turbidity.

Subsequently, the Forward method of the Ordistep function was utilized to select the most significant explanatory variables (p=0.05; 999 permutations). This analysis was specifically based on biotic and abiotic data corresponding to the lake's surface. The use of adjusted R-squared values in the RDA results was favored, as it accounts for the influence of variable count on explanatory power (Boccard et al., 2011). All analyses were conducted using the R statistical software (R Core Team, 2023) and involved the statistical packages "*Vegan*" (Dixon 2003), "*factoextra*" (Kassambara & Mundt, 2017), "*factoMineR*" (Lê et al., 2008), "*betareg*"

(Zeileis et al., 2016), "*betapart*" (Baselga & Orme, 2012) and "*glm*" (Calcagno & Mazancourt, 2010).

3. Results

3.1. Environmental and limnological characterization of Lake Ingá

During the initial sampling series (dry period) and in the ten days preceding the commencement of sampling, no precipitation occurred. In the subsequent sampling series (rainy period), there were seven instances of localized rainfall, with precipitation ranging from 5mm to 35mm. In the context of a subtropical environment, water temperature also emerged as a parameter of seasonal significance. In the dry period, lower temperatures ranging from 18.9 to 23.5 ºC were observed. Conversely, in the rainy season, water temperature remained consistently high throughout the entire sampling series, fluctuating between 27.1 and 29.8 ºC. Among the various nutrients present in the water surface, the concentration of ammonium ion (NH_4) increased nearly fourfold during the rainy season (average concentration of 68.51 μg L⁻¹) compared to the dry period (average concentration of 246.6 μg L⁻¹) (Table 1).

The first two axes of Principal Component Analysis (PCA) accounted for 62.6% of the variability in the environmental data, highlighting periods of higher and lower rainfall. On Axis 1 (46%), a negative correlation was observed between pH (-0.59), dissolved oxygen (-0.92), and NO_3-N (-0.32) during the dry period. On the other hand, water temperature (0.76), PO_4-P (0.53), and NH_4-N (0.87) exhibited positive correlations with the rainy period (Figure 3).

Table 1. Mean, maximum and minimum values, and coefficient of variation (% in parentheses) of abiotic variables measured in Lake Ingá from May to June 2018 (dry period) and January to February 2019 (rainy period).

| Dry											
Surface	Z_{max}	Secchi	WT	DO	pH	Cond	Turb	NO3	NH4	TP	PO4
Mean	3.90	0.74	20.75	7.77	7.95	124.46	5.37	0.23	68.51	44.55	9.32
Maximum	5.50	0.85	23.50	9.59	8.80	131.40	8.90	0.50	154.47	76.52	13.46
Minimum	3.50	0.50	18.90	5.99	7.46	119.20	4.20	0.02	4.28	24.46	3.97
Coeff. var.	(0.28)	(10.0)	(15.0)	(7.0)	(23.5)	(27.0)	(5.6)	(1.4)	(1.6)	(4.5)	(3.4)
Zeu											
Mean			20.74	7.08	7.82	125.15	5.42	0.23	71.46	41.56	9.26
Maximum			23.80	9.03	8.38	132.10	6.35	0.60	147.13	72.03	13.18
Minimum			18.70	5.32	7.17	119.50	4.28	0.01	8.29	0.00	3.73
Coeff. var.			(14.3)	(7.0)	(22.7)	(27.3)	(9.0)	(1.4)	(1.8)	(3.9)	(3.2)
Botton											
Mean			20.68	5.49	7.81	125.27	5.56	0.24	85.21	43.89	9.37
Maximum			23.70	8.57	8.18	132.20	6.66	0.48	150.05	77.40	12.61
Minimum			18.70	3.24	7.06	120.00	4.51	0.03	13.26	33.46	4.22
Coeff. var.			(14.7)	(5.1)	(32.4)	(27.4)	(9.1)	(1.6)	(2.3)	(5.6)	(3.5)
Rainy											
Surface	Z_{max}	Secchi	WT	DO	pH	Cond	Turb	NO3	NH4	TP	PO4
Mean	4.15	0.79	28.33	5.47	7.40	122.30	5.45	0.11	246.66	35.34	18.98
Maximum	6.0	0.90	29.80	7.33	8.20	127.20	6.82	0.22	416.99	49.65	43.68
Minimum	4.0	0.55	27.10	2.81	6.38	115.70	4.63	0.00	21.78	21.00	8.38
Coeff. var.	1.15	(8.9)	(37.6)	(5.5)	(18.6)	(31.1)	(11.6)	(1.4)	(1.9)	(4.3)	(1.7)
Zeu											
Mean			28.15	4.01	7.36	123.83	5.02	0.09	249.63	32.82	17.60
Maximum			29.40	6.20	7.82	143.10	6.32	0.19	469.28	50.55	37.12
Minimum			26.90	0.51	6.83	116.60	0.00	0.00	0.00	0.00	0.00
Coeff. var.			(36.1)	(2.7)	(29.1)	(23.0)	(2.9)	(1.1)	(1.7)	(2.4)	(1.5)
Botton											
Mean			27.60	1.29	7.21	131.99	8.49	0.11	378.72	45.27	18.47
Maximum			29.50	5.92	7.81	196.50	33.04	0.17	1087.01	69.06	37.47
Minimum			17.50	0.12	6.56	116.60	5.05	0.07	67.01	26.98	8.21
Coeff. var.			(13.8)	(0.8)	(22.7)	(7.4)	(1.5)	(3.9)	(1.8)	(3.7)	(1.8)

Zmax= Total depth, WT= Water temperature, DO= Dissolved oxygen, pH= Hydrogenionic potential, Cond= Conductivity, Turb= Turbidity, TP= Total phosphorus.

3.2. Phytoplankton community

A total of 151 taxa were identified, distributed across 12 taxonomic groups, including 46 Chlorophyceae, 30 Cyanobacteria, 18 Euglenophyceae, 14 Zygnematophyceae, 9 Trebouxiophyceae, 8 Bacillariophyceae, 7 Coscinodiscophyceae, 6 Xanthophyceae, 4 Chlamydophyceae, 4 Cryptophyceae, 3 Chrysophyceae, and 2 Dinophyceae. The most representative genera in both sampling periods were *Desmodesmus* (Chodat) S.S. An, T. Friedl & E. Hegewald, with eight taxa, and *Monoraphidium* Kom-Legnerová, with seven taxa, both belonging to the class Chlorophyceae.

There was an increase of up to nine times in phytoplankton density and biovolume values during all rainy period samplings compared to the dry period. Conversely, species richness remained higher throughout the dry period. These three community attributes (density, biovolume, and species richness) displayed similar values in samplings taken at the
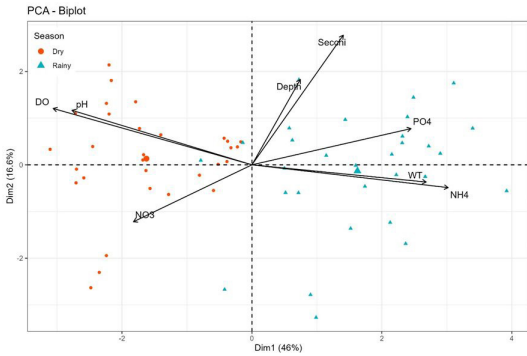
Figure 3. Dispersion of the scores of the first two axes of the PCA of the main physical-chemical variables of the water distributed by the days of sampling in the lagoon. Zmax -(Depth), dissolved oxygen- (DO), hydrogen potential-(pH), water temperature- (Temp), ammonium ion- (NH_4-N), nitrate – (NO_3-N), phosphate- (PO_4-P).

surface, euphotic zone boundary and the bottom during both study periods (Figure 4).

Phytoplankton density reached its maximum values on the third day of sampling during the rainy period (104,642 indmL^{-1}), and its minimum on the fourth day of sampling during the dry period (10,000 ind mL^{-1}). The taxonomic groups Cyanobacteria, Chlorophyceae, and Zygnematophyceae were the primary contributors to phytoplankton density in both study periods (Figure 4A). The species that contributed the most to this attribute in both sampling periods were *Raphidiopsis raciborskii* (W.) Seen. and Sub. Rajú (Cyanobacteria, MBFG VIII), *Monoraphidium contortum* (Thur.) Kom.–Legn. (Chlorophyceae, MBFG I) and *Cosmarium regnesi* Reinsch (MBFG IV) (Figure 5B).
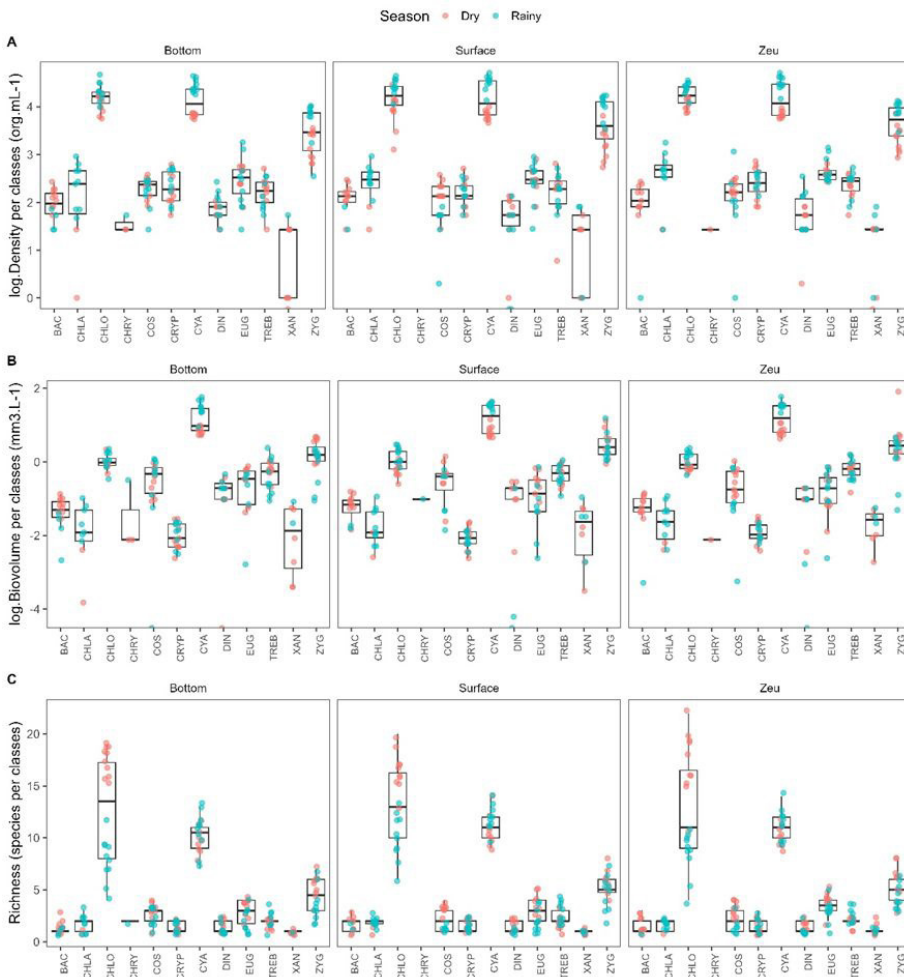
Figure 4. Mean values and standard deviations of density (A), biovolume (B), and species richness (C) in Ingá Lake. These variables were estimated during the period from May to June 2018 (dry season) and January to February 2019 (rainy season) across three strata (Surface, Euphotic Zone Boundary (Zeu), and Bottom). Biovolume and density values were logarithmically transformed.
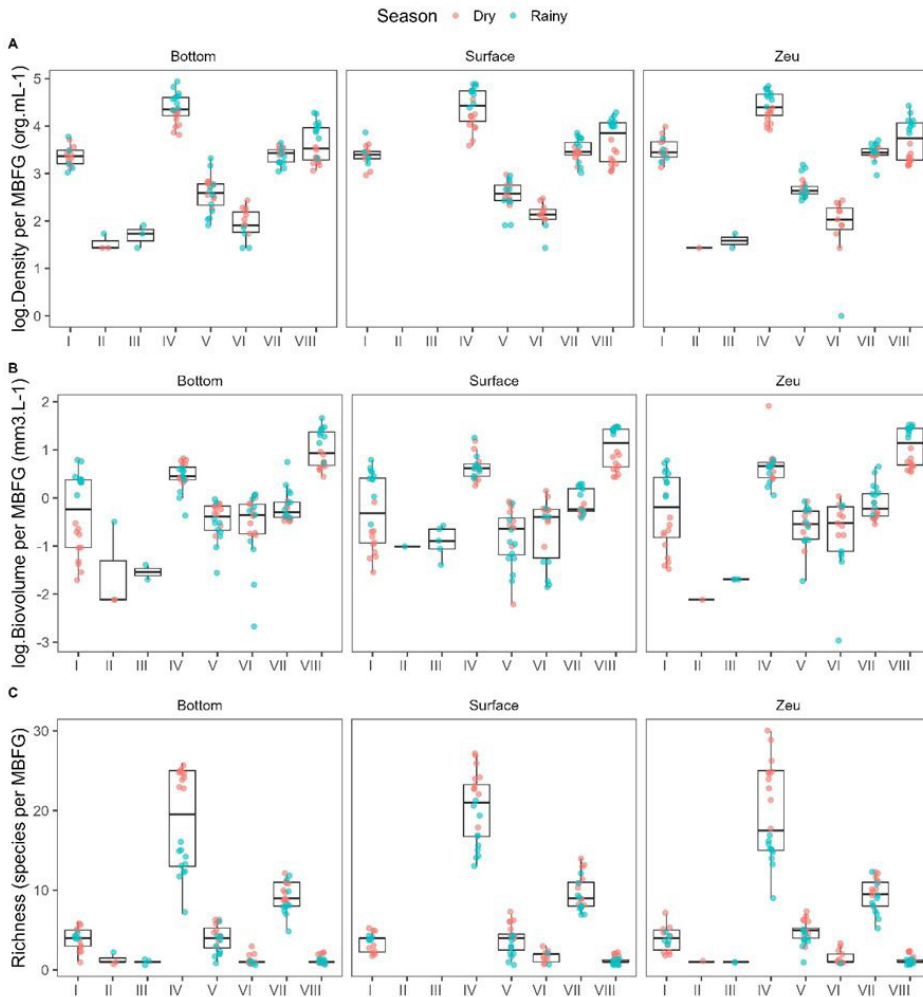
Figure 5. Mean values and standard deviations of density (A), biovolume (B) and species richness (C) in Ingá Lake by Functional Groups Based on Morphology (MBFG). These variables were estimated during the period from May to June 2018 (dry season) and January to February 2019 (rainy season) across three strata (Surface, Euphotic Zone Boundary (Zeu), and Bottom). Biovolume and density values were log-transformed.

Phytoplankton biovolume was higher during the rainy period, showing considerable variation among sampling days. Maximum values were observed on the third day of sampling during the rainy period (85.0 mm³ L⁻¹), while the lowest value was observed on the last day of sampling during the dry period (7.89 mm³ L⁻¹). The taxonomic groups Cyanobacteria (MBFG VII and VIII) and Zygnematophyceae (MBFG IV) were the main contributors to this attribute in both study periods (Figures 4B and 5B). The species that contributed the most to biovolume during the dry period were *Cosmarium regnesi* Reinsch and *Staurodesmus* sp., while during the rainy period, it was *R. raciborskii* (Cyanobacteria).

Regarding species richness, there was minimal variation within each sampling period. However,

the dry period exhibited the highest species richness values on all sampling days, with the highest value observed on the last day of sampling in that period (52 taxa). The taxonomic classes Chlorophyceae (MBFG IV) and Cyanobacteria (MBFG VIII) were the primary contributors to this attribute in both study periods (Figure 4C).
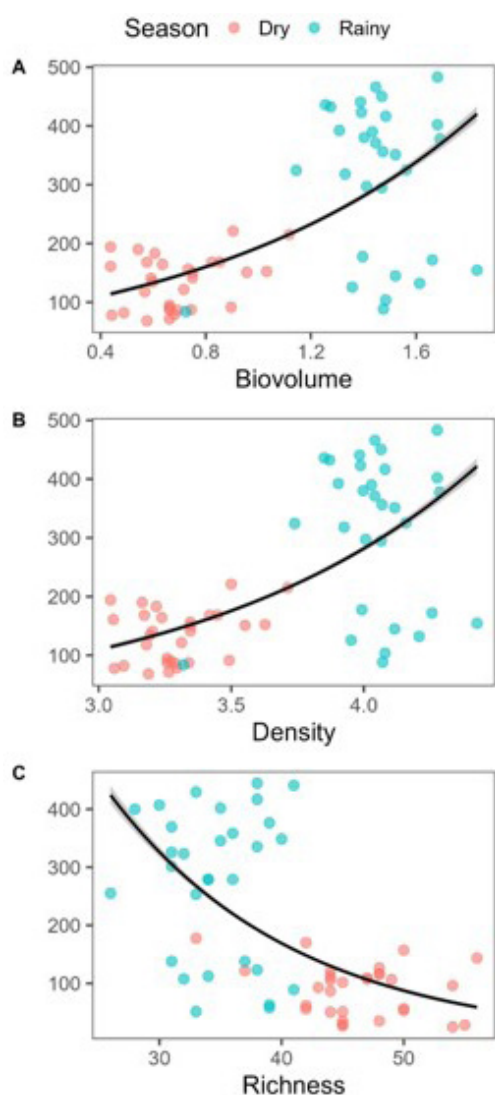
The Generalized Linear Models (GLMs) revealed a significant and positive increase in both density and biovolume over time, primarily influenced by elevated concentrations of ammonium (NH_4) and water temperature (Table 2), leading to the differentiation between the two sampling periods. However, the GLMs indicated a decrease in species richness from the dry to the rainy period (Figure 6).

The Redundancy Analysis (RDA), which accounted for 91% of the variance in the data,
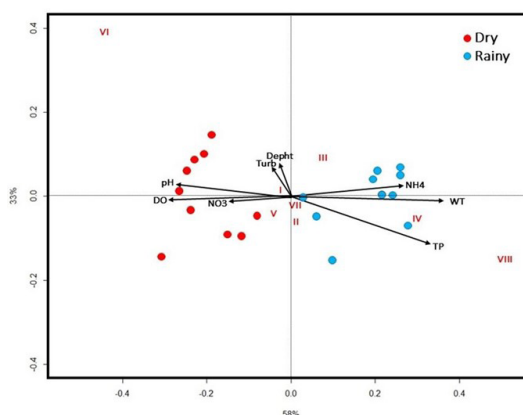
Table 2. Results of the Generalized Linear Models (GLMs) for phytoplankton density, biovolume, and species richness in Ingá Lake. Values of p less than 0.01 (in bold) were considered significant.

Density	Estimate	Std. Error	z value	*p*
(Intercept)	1.18	0.1111	10.6	**<0.001**
NH_4-N	4.16	0.0006	0.06	**<0.001**
WT	6.29	0.005	1.06	**<0.001**
Biovolume	Estimate	Std. Error	z value	*p*
(Intercept)	0.6735	0.0385	17.4	**<0.001**
NH_4-N	0.0001	0.0002	0.66	**0.048**
WT	0.0231	0.0021	10.7	**<0.001**
Richness	Estimate	Std. Error	z value	*p*
(Intercept)	3.84	0.0309	124.3	**<0.001**
NH_4-N	-0.0001	0.0002	-0.656	0.512
WT	-0.0083	0.0018	-4.517	**<0.001**

Figure 7. Biplot diagram for the Redundancy Analysis (RDA) depicting the relationship between phytoplankton biomass categorized into the eight Morphologically-Based Functional Groups (MBFG) and the selected environmental variables. Blue circles correspond to the rainy period, and the red circles correspond to the dry season. The analysis was conducted using only the data corresponding to the lake's surface. Turb- Turbidity, DO- Dissolved oxygen, NO3- Nitrite, NH4- Ammonium, TP- Total phosphorus, WT- Water temperature.

Figure 6. Generalized Linear Models (GLM) illustrating the correlation between biovolume (A), density (B) and species richness (C) in Ingá Lake during two sampling periods (dry and rainy). The line and shaded regions depict the values forecasted by the models along with the 95% confidence interval.

revealed a temporal gradient of phytoplankton species throughout the study period (Axis 1 = 58%; Axis 2 = 33%; P < 0.001) (Figure 7). Axis 1 highlighted the differentiation between the two sampling periods, with samples from the rainy period positioned on the right side of the diagram, displaying higher values of phytoplankton biovolume. This distribution pattern is primarily linked to the functional groups VIII and IV, which are associated with higher values of water temperature, total phosphorus, and ammonium. On the left side of the diagram, the prominent presence of functional groups I, V, and VI is notable, which are associated with higher values of pH, dissolved oxygen, and nitrate.

4. Discussion

The classification of morphologically based functional groups (MBFG) proved to be an effective indicator of the environmental and seasonal conditions of lake of Ingá Park. The MBFGs responded to changes in environmental conditions, especially seasonality, thus corroborating our initial hypotheses. The lake in Ingá Park exhibited dynamic behaviour, with high concentrations of nutrients, especially total phosphorus, where its limnological characteristics were possibly influenced by the seasonality of rainfall (Cunha et al., 2013). Seasonality played a significant regional climatic role in the lake's dynamics, as water input into the system could have led to habitat expansion, resulting in alterations in the physical environment and aquatic communities (Nabout & Nogueira, 2011).

Although high species richness values are usually associated with the absence of dominance, it's important to highlight that even in episodes of cyanobacterial dominance, a significant contribution from Chlorophyceae and other groups considered more environmentally demanding for species richness can be observed, as is the case with the presence of Xanthophyceae taxa (Train et al., 2005; Tucci et al., 2006). Understanding how the environment influences the composition and richness of phytoplankton species becomes a challenge of paramount importance in mitigating the impacts of anthropogenic activities and climate changes on the environment, ensuring the continuity of ecosystem services. In this context, special attention must be given to changes in species composition within the phytoplankton, leading to the dominance of Cyanobacteria, given that their effects on the environment's metabolism will directly interfere with the diversity of water resource uses (Catherine et al., 2016).

The Chlorophyceae and Cyanobacteria groups, as well as MBFG IV and VII, were the main contributors to species composition, encompassing about 50% of all identified taxa. These groups have a broad distribution and play an important role both in the composition and other attributes of the phytoplankton community. The Chlorophyceae (MBFG IV), composed of small green algae without specializations, and the Cyanobacteria (MBFG VII), composed of large mucilaginous cyanobacteria, are groups formed by organisms efficient in capturing resources from the environment, mainly nutrients such as nitrogen and phosphorus, which may explain the high representativeness of these groups in Ingá Lake. Furthermore, the Chlorophyceae (MBFG IV), due to their diminutive size, have greater ease of dispersal and a rapid population generation rate. Conversely, Cyanobacteria (MBFG VII) exhibit morphological specializations such as mucilage and aerotopes, which provide organisms in this group with greater ease in remaining in the surface layer of the lake and thus ensuring a greater advantage in light capture (Silva et al., 2022). These groups are frequently described in eutrophic tropical and subtropical environments (Borges et al., 2008; Fabrin et al., 2020; Gentil et al., 2008; Tucci et al., 2006).

Seasonal variations in the structure of phytoplankton communities in subtropical environments are often related to large-scale environmental changes, such as those in drainage basins, as well as increases in water nutrient concentrations, variations in precipitation, and temperature. These changes induce local alterations in the physical and chemical conditions of the lake water, which in turn influence the structure of the phytoplankton community (Cupertino et al., 2019; Dantas et al., 2010; Figueiredo & Giani, 2009). It is important to consider that the main sources of allochthonous nutrient inputs in urban lakes are clandestine discharges of domestic sewage, released into the storm drainage systems, and runoff of surface water from the entire drainage basin during the rainy season (Nardini & Nogueira, 2008; Naselli-Flores et al., 2007).

In the studied lake, a fourfold increase in NH4-N concentrations and a twofold increase in PO4-P concentrations were observed during the rainy season compared to the dry period. These inorganic nitrogen and phosphate compounds are the most important sources for phytoplankton growth, and their increase can have significant impacts on local primary productivity (Domingues et al., 2011). This may have directly influenced the increase in phytoplankton density and biovolume during the rainy season. The light and nutrient availability are the main factors that regulate phytoplankton growth, typically being limiting in eutrophic environments (Reynolds 2006; Nardini & Nogueira, 2008, Perbiche-Neves et al., 2011).

The nanoplanktonic fraction of phytoplankton (<20 µm), primarily Chlorophyceae (MBFG I and IV), played a significant role in the density values of the Ingá Lake. The contribution of these groups deserves attention, as they are algae widely distributed in nutrient-rich environments (Gentil et al., 2008). This fraction of the phytoplankton community is favored mainly due to their high surface-to-volume

ratio, which enables rapid and efficient nutrient absorption and a high reproduction rate, allowing for the replenishment of organisms in the face of predation events (Carrick et al., 2017; Naselli-Flores et al., 2007). Therefore, the contribution of nanoplanktonic algae to the system's metabolism is crucial under conditions of microplanktonic cyanobacterial dominance (>80 μm), as these organisms, despite representing low biomass values due to their small size, effectively participate in energy transfer processes to higher trophic levels (Meira et al., 2017).

The dominance in density and biovolume of Cyanobacteria, especially MBFG VII and VIII, aligns with what is commonly reported in the literature in reservoirs and urban lakes in tropical and subtropical regions (Figueiredo & Giani, 2009; Gamelgo et al., 2009; Jati et al. 2017; Lv et al., 2011; Qin et al., 2019; Silva et al., 2022; Van Dam et al., 2018). These organisms have high adaptation in ecosystems with high nutrient concentrations (Padisák et al., 2009; Reynolds, 2006) and even in less nutrient-rich environments, they exhibit high efficiency in exploiting environmental resources (Aubriot & Bonilla, 2018). Moreover, they may possess other competitive advantages over other phytoplankton groups, such as the ability to fix atmospheric nitrogen (MBFG VIII) and the capability to regulate their position in the water column due to the presence of aerotopes and mucilaginous sheath (MBFG VII) (Li et al., 2018).

The determinants for the dominance of MBFG VIII, represented by the heterocytous cyanobacterium *R. raciborskii,* were likely the synergy between tolerance to the isothermal water column, efficient growth in low light availability, and affinity for high concentrations of ammonium ions (Reynolds, 2006, Zohary et al., 2010). According to Dantas et al. (2010), species of bloom-forming Cyanobacteria can coexist, alternating in response to changes in the physical and chemical conditions of the water, with colonial species predominating during periods of thermal stratification, which may be replaced by filamentous species dominant during periods of water column isothermy. However, it's important to highlight that these strategies are not mutually exclusive, and colonial species can occur in isothermal environments, while filamentous species can occur in thermally stratified environments. In addition to its toxigenic potential, *R. raciborskii* has large dimensions and represents a low-quality food resource for zooplankton (Ferrão-Filho et al., 2002; Ghadouani et al., 2003; Panosso et al., 2003).

These characteristics make it difficult to control these populations through predation, favoring the onset of blooms and the accumulation of its biomass (Fialkowska & Pajdak-Stós, 2002). Population of *R. raciborskii* observed in these studies consisted of spiral, coiled, and a few straight morphotypes, with the absence of heterocytes. The filament's morphology, the presence of specialized cells such as heterocytes and akinetes, their dimensions, and position are important characteristics for identifying this taxon (Saker et al., 1999). Despite morphological differences, molecular analyses confirm that these morphotypes belong to the same species (Bittencourt-Oliveira et al., 2012) and reflect the extensive phenotypic plasticity that the taxon exhibits in response to environmental variations (Saker et al., 1999; Shafik 2003), with morphotypes occurring simultaneously in samples (Dantas et al., 2010). Among the bloom-forming and toxin-producing Cyanobacteria, *R. raciborskii* is among those causing significant concern, as it can produce neurotoxins (saxitoxins), which act directly on the central nervous system, and hepatotoxins (cylindrospermopsins), which cause liver abnormalities (Calijuri et al., 2006). Although analyses of the presence of these toxins in the water of Ingá Lake were not conducted, the mere presence of this taxon in high biomass is already a cause for alert.

According to resolution 357/2005 of CONAMA (Conselho Nacional de Meio Ambiente) (Brasil 2005), the presence of Cyanobacteria has a maximum limit of 10 $mm^3.L^{-1}$ for the water body to be used for secondary contact recreation (such as boats, pedal boats, and kayaks). In the case of Ingá Lake, this value was exceeded up to 8 times during the rainy period, which coincides with summer when the population frequents the lake for leisure activities, elevating Ingá Lake to Class 4, where the environment can only be used for landscaping purposes.

5. Conclusions

Therefore, stricter regulation of secondary contact activities in the lake is necessary to protect the population from potential contamination. Additionally, systematic analyses to identify, classify, and quantify cyanotoxins in the water of Ingá Lake are important, along with monitoring these toxins considering seasonal variations in rainfall, to guide the management of this environment.

The restoration of Ingá Lake should be approached through actions that address human

impacts in the drainage basin. Soil impermeability and human occupation in the basin significantly contribute to increased nutrient input. Furthermore, overexploitation of groundwater for population supply leads to decreased water volumes in the aquatic environment and deterioration of water quality (Nardini & Nogueira, 2008; Naselli-Flores, 2008).

Actions solely focused on reducing nutrients in the lake, without broader measures in the drainage basin, would only offer temporary solutions (Naselli-Flores, 2008). Reducing phytoplankton biomass and the proliferation of cyanobacteria in Ingá Lake depends on decreasing nutrient inputs and renewing the lake's water. Therefore, by reducing nutrient inflow and revitalizing the environment, it is possible to achieve environmental rejuvenation and promote new succession events within the community.

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