Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Original Article
Acta Limnologica Brasiliensia, 2021, vol. 33, e24
https://doi.org/10.1590/S2179-975X10320
ISSN 2179-975X on-line version

Phytoplankton functional groups in shallow aquatic ecosystems from the semiarid region of Brazil

Grupos funcionais fitoplanctônicos em ecossistemas aquáticos rasos na região semiárida do Brasil

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Cite as: Silva, K.R.P. et al. Phytoplankton functional groups in shallow aquatic ecosystems from the semiarid region of Brazil. *Acta Limnologica Brasiliensia*, 2021, vol. 33, e24.

Abstract: Aim: The study analyzed the potential use of the phytoplankton functional groups as an environmental bioindicator in aquatic ecosystems of Brazilian semiarid region. **Methods:** Using data collected over five years of a natural lagoon and two reservoirs, we evaluate the relationship between functional groups and environmental conditions through the multivariate approach. The Q index was applied to assess ecological status in these ecosystems. **Results:** In Panati, the temporary and natural lagoon, the partial habitat desiccation and presence of macrophytes reflected in the less nutrients concentrations and phytoplankton composition, with high biomass of coccoids Chlorophyceae, diatoms and desmids (functional groups **J**, **MP** and **N**, respectively). Taperoá and Soledade reservoirs presented high cyanobacteria contribution, however the biomass and contribution of cyanobacteria in Taperoá ($\mathbf{S_N}$, $\mathbf{S_1}$) were lower than in Soledade. In this reservoir, cyanobacteria were more abundant, alternating in dominance ($\mathbf{L_O}$, **M**, $\mathbf{L_M}$, $\mathbf{S_N}$, $\mathbf{S_1}$). According to tendencies revealed by Redundancy Analysis (RDA), the main driving abiotic factors on the phytoplankton functional groups were pH, nutrients and light availability. As expected, phytoplankton composition directly influenced the Q index result, showing mostly bad to tolerable conditions in Soledade, medium to good in Taperoá and good to excellent in Panati. **Conclusions:** The Q index was a good tool to assess the water quality and ecological status in aquatic ecosystems from the Brazilian semiarid region, reflecting the influence of natural control mechanisms on the harmful cyanobacteria blooms in temporary ecosystems.

Keywords: cyanobacteria dominance; reservoirs; physical disturbances; Q index; water quality.

Resumo: Objetivo: O estudo analisou o potencial uso dos grupos funcionais do fitoplâncton como bioindicador ambiental em ecossistemas aquáticos do semiárido brasileiro. **Métodos:** Usando dados coletados de uma lagoa natural e dois reservatórios ao longo de cinco anos, avaliamos a relação entre grupos funcionais e condições ambientais por meio de uma abordagem multivariada. O índice

Q foi aplicado para avaliar o estado ecológico desses ecossistemas. **Resultados:** Em Panati, uma lagoa temporária e natural, a dessecação parcial do habitat e presença de macrófitas aquáticas refletiram nas menores concentrações de nutrientes e na composição do fitoplâncton, com alta biomassa de Chlorophyceae cocóides, diatomáceas e desmídias (grupos funcionais **J**, **MP** e **N**, respectivamente). Os reservatórios Taperoá e Soledade apresentaram alta contribuição de cianobactérias, no entanto a biomassa e a contribuição de cianobactérias em Taperoá ($\mathbf{S_N}$, $\mathbf{S_1}$) foram menores do que em Soledade. Nesse reservatório, as cianobactérias foram mais abundantes, alternando em dominância ($\mathbf{L_O}$, **M**, $\mathbf{L_M}$, $\mathbf{S_N}$, $\mathbf{S_1}$). De acordo com as tendências reveladas pela análise de redundância (RDA), os principais fatores abióticos atuantes sobre a estrutura dos grupos funcionais do fitoplâncton foram o pH, os nutrientes e a disponibilidade de luz. Como esperado, a composição do fitoplâncton influenciou diretamente o resultado do índice Q, mostrando condições ruins a toleráveis em Soledade, médias a boas em Taperoá e boas a excelentes em Panati. **Conclusões:** O índice Q mostrou-se uma boa ferramenta para avaliar a qualidade da água e o estado ecológico de ecossistemas aquáticos do semiárido brasileiro, refletindo a influência de mecanismos naturais de controle sobre o florescimento de cianobactérias prejudiciais em ecossistemas temporários.

Palavras-chave: dominância de cianobactéria; reservatórios; distúrbios físicos; índice Q; qualidade de água.

1. Introduction

The current impacts associated with eutrophication in reservoirs and surface waters worldwide have promoted increased cyanobacteria blooms, along with consequent water quality reduction and increased turbidity (Paerl & Otten, 2013; Withers et al., 2006). In recent years, artificial eutrophication has been associated with the taxonomic, functional and phylogenetic homogenization in aquatic ecosystems (Alexander et al., 2017). Consequently, the biodiversity and native species may be drastically reduced, along with the environmental services such as water for supply, irrigation and multiple other uses (e.g. Bennett et al., 2015).

In dry regions around the world, the high demand for public water supply is accompanied by the emergence of extremes and prolonged droughts (Mendonça Júnior et al., 2018). The main hypothesis indicates that the climate changes are dramatically decreasing rainfall and increasing evapotranspiration in dry zones around the world (Li et al., 2019), influencing the aquatic ecosystems distribution, as well as reducing the water level (Brasil et al., 2016). In this sense, the Brazilian semiarid region is characterized by extreme climatic conditions, with high temperatures (27-29 °C), strong sunlight and high evaporation rates associated with the lowest and most irregular rainfall indices in the country (Vieira et al., 2009). Under these conditions, aquatic ecosystems are subject to alternating periods of drought and rainfall, with a drastic reduction of water level associated with the increasing eutrophication of reservoirs (Chaves et al., 2013).

Over the last decades, the phytoplankton community received notoriety as one of the five biological groups to estimate the ecological quality of aquatic bodies according to the Water Framework Directive (WFD) on the European continent. The WFD contrasts with many models generated over time because it relies on the ecological structure and function of aquatic ecosystems, with biological elements (fish, invertebrates, macrophytes, phytobenthos and phytoplankton) as the basis for assessing ecosystem status, hydromorphology, and physical and chemical parameters as the supporting elements (e.g., European Union, 2000; Bennion & Battarbee, 2007). Such change in assessment was crucial because of the accuracy of biological indicators as phytoplankton in reflecting ecosystem status and anthropogenic pressures, thus supporting the characterization of aquatic ecosystems (Borics et al., 2007; Belkinova et al., 2014).

Historically, phytoplankton studies were based on taxonomic classification. The emergence of functional classification in recent decades, indicated the relevance of this approach to assess the ecological status of the aquatic ecosystems over the world (Pasztaleniec & Poniewozik, 2010; Sevi̇ndi̇k et al., 2017), according to the characteristics physiological, morphological, and ecological of the species accommodated in polyphyletic groups (Reynolds et al., 2002; Padisák et al., 2009). The use of phytoplankton associations in the historical reconstruction of water quality through the Q index indicates that this community is sensitive to changes in the trophic state presented by the ecosystem (Hajnal & Padisák, 2008). The functional approach is strictly associated with the Q index concept, indicating through the relative contribution of the functional groups to the total biomass the degree of pollution and the reference conditions (Padisák et al., 2006).

The Q index includes phytoplankton associations, which are very sensitive to species selected by environmental characteristics and biogeographic aspects of the ecosystem (Padisák et al., 2006; Becker et al., 2009) and are a good tool for biomonitoring. The index has been replicated successfully in aquatic ecosystems from different parts of the world (Szilágyi et al., 2008; Crossetti & Bicudo, 2008; Hajnal & Padisák, 2008; Pasztaleniec & Poniewozik, 2010; Santana et al., 2017), including places with specific characteristics, i.e., saline or naturally eutrophic reservoirs in semiarid areas (Silva & Costa, 2015). This is due to the fact that establishment of reference conditions has greater predictive value when associated with the functional groups approach (e.g., Padisák et al., 2006).

Herein, the main objectives were to analyze the dynamics of the functional groups and to evaluate the Q index applied as a tool to assess ecological status and water quality in three shallow ecosystems with multiple uses in the semiarid region of Brazil.

2. Material and Methods

2.1. Study area

The aquatic ecosystems are situated in the Taperoá river basin, Northeast region (Paraíba State), Brazil (Figure 1). Located in the central part of physiographic region of the Borborema Plateau, this region is dominated by Caatinga vegetation and has a hot semiarid climate (Bsh type), with mean annual temperature slightly higher than 26.5 °C and annual precipitation around 400 mm, being one of the driest sites in Brazil (Alvares et al., 2014). Even during the rainy season, which usually occurs between November and April, rainfall distribution is uneven and does not occur in some years, causing severe droughts (EMBRAPA, 2019). The main use and land cover in the Taperoá river basin are agriculture (pastures and small crops), which comprises 71.3% of the total area, and the Caatinga vegetation (26.5%) (Seabra et al., 2014).

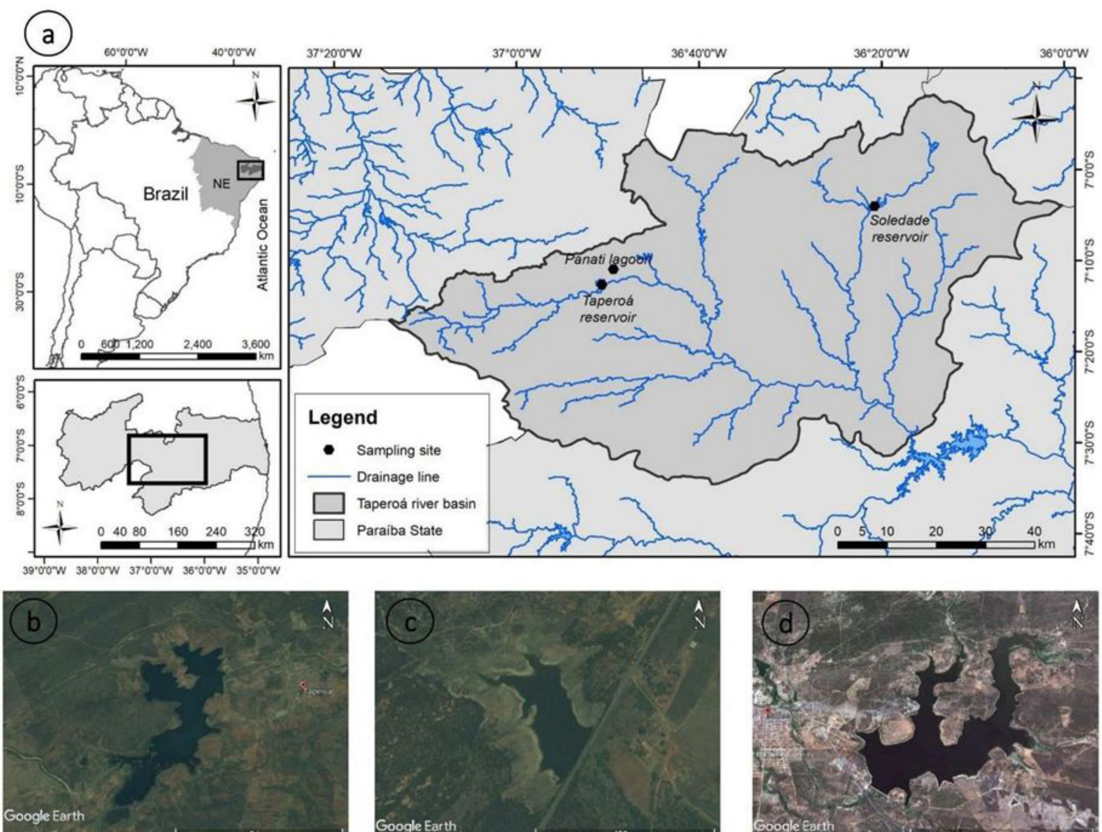

Figure 1. (a) Localization of the Taperoá river basin (Paraíba State, Brazil) and the three aquatic ecosystems studied; satellite images (Google Earth Pro Platform) of the (b) Taperoá reservoir, (c) Panati lagoon and (d) Soledade reservoir.

Three shallow environments (≤ 15 m) were selected for this study: two reservoirs and one natural lagoon. The Soledade reservoir (07°04'01" S, 36°20'43" W) is located on the Borborema Plateau, 530 m above sea level, in the Soledade municipality. It has a maximum depth of 15 m, a capacity of 27,058,000 m^3 (AESA, 2019a), a total drainage area of 315 km^2 and is used for rural water supply, animal consumption and irrigation (ANA, 2017). The Taperoá II reservoir (07°12'39" S, 36°50'37" W, herein referred to as Taperoá reservoir), situated in the Taperoá municipality, has a maximum depth of 5.7 m, a capacity of 15,148,900 m^3 (AESA, 2019a), a total drainage area of 591 km^2 and is used for urban and rural water supplies, animal consumption and irrigation (ANA, 2017). The Panati lagoon (07°10'56" S, 36°49'22" W), also located in the Taperoá municipality, is a small natural lagoon situated at 560 m above sea level. It is a closed depressional lagoon (Souza & Abílio, 2006), with a maximum depth of 1.5 m (rainy season) and abundance of aquatic macrophytes in the littoral zone (Freitas & Crispim, 2005), without connection with rivers.

2.2. Sampling and analyzed variables

Water and phytoplankton community samples were collected at intervals ranging between one and three months, over a period of five year (November 2005 to December 2010, n = 29 in each reservoir and in the lagoon). Samples were collected from the subsurface of the limnetic zone.

Rainfall data of the region and reservoir volumes (Soledade and Taperoá) from the survey period were obtained from the website of the Executive Agency for the Management of Waters of the State of Paraíba (AESA, 2019a, b).

The water temperature and pH were measured using a FAC thermistor and potentiometer instrument, respectively. Water transparency was estimated using a Secchi disk and the euphotic zone (Z_{eu}) calculated by multiplying the value obtained from the Secchi disk by 2.7 (Cole, 1994). Unfiltered water samples were used to analyze total phosphorus (TP) (APHA, 2005). Using filtered water samples, soluble reactive phosphorus (SRP) was determined through the ammonium molybdate methodology (APHA, 2005); ammonium ($N\text{-}NH_4$), nitrite ($N\text{-}NO_2$) and nitrate ($N\text{-}NO_3$) and were obtained using the phenol, diazotization of sulfanilamide-NED, and cadmium reduction techniques, respectively (APHA, 2005). The Trophic State Index (TSI) was measured using TP concentrations and Secchi disk depth, following Lamparelli (2004).

Samples for analysis of the phytoplankton community were preserved in aqueous acetic Lugol's solution (4%). The quantitative analysis of the phytoplankton was performed following Utermöhl (1958) and the settling time followed Lund et al. (1958). The phytoplankton biovolume was calculated using geometrical shapes (25-30 individuals per species) following Hillebrand et al. (1999) and Sun & Liu (2003). The results are expressed in biomass, that is, fresh weight units, where 1 mm^3 L^{-1} = 1 mg L^{-1} (Wetzel & Likens, 2000). The functional groups (FG) were defined by the species contributing to > 1% of the total biomass in the sample (Reynolds et al., 2002; Padisák et al., 2009).

2.3. Ecological status

The assembly index (Q index) (Padisák et al., 2006) was used to describe the water quality of the two reservoirs and the Panati lagoon. The calculation of the index considers the relative contribution of functional groups in the total biomass and a factor F (ranging from 0 to 5) is established for each functional group occurring in each reservoir/lagoon. A higher factor F value was determined for functional groups that are typically found under more pristine conditions of the corresponding water body, and lower F values commonly occur in less pristine conditions. The index provides five levels of ecological status classification for the aquatic environment: 0-1: bad; 1-2: tolerable; 2-3: medium; 3-4: good; 4-5: excellent (Padisák et al., 2006).

2.4. Statistical analysis

Physical and chemical variables of water were analyzed using descriptive statistics. The Redundancy Analysis (RDA) was applied to evaluate the relationship of functional groups with eight abiotic variables of the water of the studied environments. The RDA was selected based on the length of the first axes through a detrended correspondence analysis (DCA) applied to the matrix of functional groups. The data was previously transformed by log (x + 1). The VIF (variance inflation factor) function was used to check if there was collinearity between abiotic variables (all variables were kept in RDA due to the low VIF: < 5). Lastly, the ANOVA applied to RDA-analysis was performed to verify the significance of the result of ordination. The analyses were carried out in R version 3.5.1 (R Core Team,

2018) using the *vegan* (Oksanen et al., 2019) and *fmsb* (Nakazawa, 2019) packages.

3. Results

3.1. Climatic, hydrological and abiotic variables

Rainfall was scarce during most months over the study period (0 to 50 mm). During the rainiest months (February, March, April and May, except 2010), monthly rainfall volumes ranged between 100 and 390 mm. Overall, the monthly precipitation was greater in Taperoá than the Soledade region (Figure 2a, b).

The Soledade reservoir presented the lowest water storage volumes between Nov/2005 (9.7×10^6 m^3) and Dec/2007 (2.7×10^6 m^3), period with less than 36% of the maximum capacity. The rains of March and April/2008 helped fill the reservoir, which reached 100% capacity (2.7×10^7 m^3). However, a decrease in water stored in the following months promoted a decrease of 50% of the maximum capacity (Figure 2a). In the Taperoá, the stored volume showed greater oscillation between the rainy and dry season than in Soledade. In general, the volume was higher than 70% (1.0×10^7 m^3) of the maximum capacity during most months. The increased water storage occurred in the rainy months, reaching 100% capacity in Jun-Jul/2006, Apr-Jun/2008 and overflowing in May/2009 (Figure 2b).

Panati lagoon and the reservoirs presented warm (mean: > 25.5 °C) and alkaline waters (mean: > 7.7). Panati and Taperoá exhibited clear waters throughout all study years (mean Z_{eu}: 0.72 - 1.2 m and mean Z_{eu}: 1.81 - 2.8 m, respectively) (Table 1). Potential light limitation was observed in Soledade reservoir between 2006 (mean Z_{eu}: 0.73 m) and 2008 (mean Z_{eu}: 0.84 m), improving in 2009 (mean: Z_{eu}: 2.0 m).

In general, the highest mean concentrations of dissolved inorganic nutrients were identified in Soledade and Taperoá reservoirs, especially for SRP (48.9 µg.L^{-1} and 99.6 µg.L^{-1}, respectively) and NO_3 (755.5 µg.L^{-1} and 515.3 µg.L^{-1}, respectively). The mean concentrations of TP were higher in

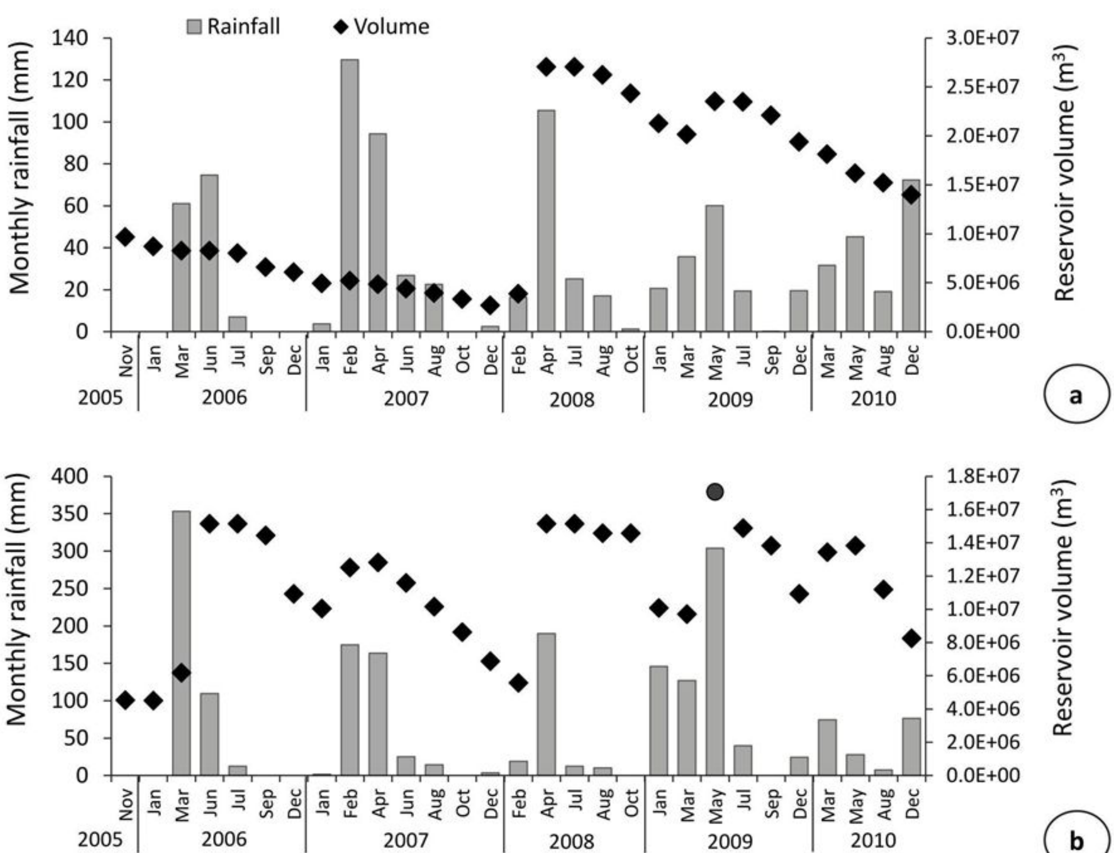

Figure 2. (a) Total accumulated rainfall in Soledade municipality and volume of water stored in Soledade reservoir; (b) total accumulated rainfall in Taperoá municipality and volume of water stored in Taperoá reservoir. The circle symbol in the volume of the Taperoá reservoir indicates overflow of water.

Soledade (> 197 μg L^{-1}) and Taperoá (most > 259 μg.L^{-1}) reservoirs (Table 1).

The Trophic State Index (TSI) maintained a slight variation trend over time in all ecosystems. Overall, Soledade showed hypertrophic conditions in most of the study months, while in Taperoá and Panati eutrophic to hypereutrophic conditions were more persistent. Mesotrophic conditions were recorded in some months in Taperoá (Jun-Jul/2006, Oct/2007) and Panati (Jun-Jul/2006, Mar-May/2009) (Figure 3).

3.2. Functional groups distribution and ecological condition (Q index)

A total of 55, 61 and 88 descriptor species were identified in Soledade, Taperoá and Panati, respectively, distributed in 19, 16 and 17 functional groups, respectively (Table 2).

High phytoplankton biomass was observed in Soledade, especially in 2006 (41.5 to 160.3 mg.L^{-1}) and 2007 (11.5 to 62.1 mg.L^{-1}) (Figure 4a). Dominant functional groups represented by colonial Cyanobacteria was observed in this reservoir, between these $\mathbf{L_O}$ (mainly *Coelosphaerium* sp.) in Jan/2006, **M** [mainly *Microcystis aeruginosa* (Kützing) Kützing] in Feb/2007 and $\mathbf{L_M}$ (mainly *Coelomoron tropicale* P.A.C.Senna, A.C.Peres & Komárek) between August and December 2007. Among filamentous cyanobacteria, the dominant groups were $\mathbf{S_1}$ [*Planktothrix agardhii* (Gomont) Anagnostidis & Komárek, *Pseudanabaena moniliformis* Komárek & Kling, *Geitlerinema* sp., *Romeria* sp.] in August 2008 and December 2009 to May 2010 and $\mathbf{S_N}$ [*Raphidiopsis raciborskii* (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique & Salerno] between March and July 2009. Diatoms were also dominant in June 2008 [**P** group, mainly *Aulacoseira granulata* (Ehrenberg) Simonsen] and August and December 2010 (**D** group, mainly *Nitzschia incurva* var. *lorenziana* R. Ross) (Figure 5a).

In contrast, the phytoplankton biomass in the Taperoá reservoir was lower than 1.0 mg.L^{-1} in most of the months studied (Figure 4b). Filamentous cyanobacteria grouped into $\mathbf{S_N}$ (mostly *Raphidiopsis raciborskii*) and $\mathbf{S_1}$ (mainly *Planktothrix agardhii*) stood out especially in January 2006, January and August 2007, August 2008 and May 2009. Diatoms were dominant during many months of the study: April and June 2007, October 2008 to March 2009 and July 2009 (mainly by *Pinnularia viridis*, *Surirella robusta*, *Navicula* sp.- **MP** group) and March 2010 (*Nitzschia longissima* and *N. obtusa* - **D** group). The functional group **P** [mainly *Closterium* sp. and *Paralia sulcata* (Ehrenberg) Cleve] was abundant in many months, presenting dominance in July 2006 (Figure 5b).

In Panati the biomass ranged from 0.7 and 30 mg.L^{-1} in most months, however the largest biomass, composed of colonial and cenobial Chlorophyceae, were recorded between October and December 2007 and September 2009 (69.6, 84.1 and 139.4 mg.L^{-1}, respectively) (Figure 4c). Therefore, unlike Soledade and Taperoá reservoirs, dominance of Chlorophyceae accommodated into **J** was verified between August 2007 and February

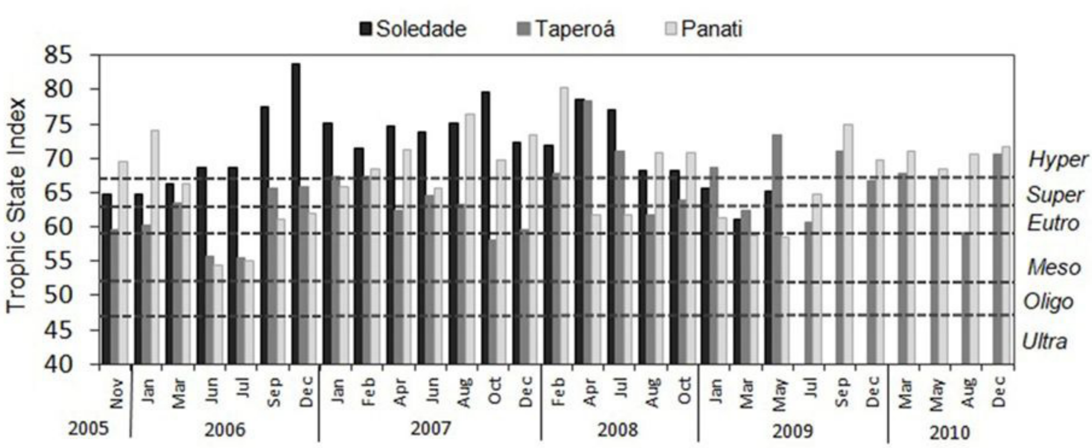

Figure 3. Trophic State Index (TSI) of the Soledade and Taperoá reservoirs and Panati lagoon from November 2005 to December 2010. Legend: Ultra (ultraoligotrophic), Oligo (oligotrophic), Meso (mesotrophic), Eutro (eutrophic), Super (supereutrophic), Hyper (hypertrophic). Missing data (total phosphorus) in the Soledade reservoir from Jul/2009 to Dec/2010.

Table 1. Limnological variables (mean and standard deviation) in three shallow aquatic ecosystems of semiarid region, Brazil. Nov/2005-2006 (n = 7), 2007 (n=7), 2008 (n=5), 2009 (n=6), 2010 (n=4). - indicates missing data.

Variables	Soledade reservoir					Taperoá reservoir					Panati lagoon				
	Nov/ 2005-2006	2007	2008	2009	2010	Nov/ 2005-2006	2007	2008	2009	2010	Nov/ 2005-2006	2007	2008	2009	2010
Temperature (°C)	26	26.1	27	27.1	26.5	25.8	26.2	26.2	26.2	26.2	27.2	27.1	26.1	28.7	27.4
	± 1.1	± 1.8	± 2.6	± 1.4	± 2.0	± 1.0	± 1.5	± 4.2	± 1.2	2.4	± 0.9	± 1.6	± 1.3	± 2.3	± 1.4
pH	9.2	8.9	8	8.3	8.6	8.1	8.2	8.1	7.9	8.1	7.7	8.3	7.9	8.3	8.3
	± 0.2	± 0.5	± 0.5	± 0.4	± 0.2	± 0.3	± 1.1	± 0.4	± 0.2	± 0.7	± 0.4	± 0.9	± 0.5	± 0.5	± 0.3
Transparency (m)	0.27	0.29	0.31	0.74	0.45	0.83	1.03	0.67	0.75	0.8	0.54	0.35	0.48	0.71	0.5
	± 0.14	± 0.11	± 0.18	± 0.32	± 0.13	± 0.36	± 0.27	± 0.39	± 0.25	± 0.14	± 0.36	± 0.19	± 0.38	± 0.33	± 0.11
Z_{eu} (m)	0.73	0.8	0.84	2	1.22	2.23	2.8	1.81	2.03	2.16	0.95	0.72	0.86	1.2	0.87
	± 0.37	± 0.30	± 0.48	± 0.87	± 0.35	± 0.96	± 0.73	± 1.06	± 0.68	± 0.38	± 0.45	± 0.31	± 0.45	± 0.37	± 0.16
$N\text{-}NO_3$ (μg.L^{-1})	11.7	172	108.8	755.5	-	27.2	198.3	65	515.3	17	55.2	61.5	61.3	201.3	18.3
	± 10.6	± 193.5	± 80.9	± 582.7		± 39.0	± 194.3	± 29.4	± 450.9	± 31.8	± 72.0	± 85.4	± 45.6	± 138.1	± 34.4
$N\text{-}NO_2$ (μg.L^{-1})	115	44	73.8	19.2	-	13	51.1	33.6	38.8	2.7	6.9	10.2	8.7	7.5	3.1
	± 151.4	± 59.6	± 56.0	± 7.1		± 12.8	± 66.7	± 23.2	± 54.8	± 1.8	± 5.0	± 14.6	± 5.3	± 8.3	± 2.2
$N\text{-}NH_4$ (μg.L^{-1})	104.8	87.6	56.2	82.7	-	17.9	36.2	53.7	286.1	167.5	19.4	8.3	12.5	130.9	112.9
	± 123.6	± 100.0	± 76.8	± 41.4		± 26.4	± 42.9	± 89.4	± 383.9	± 332.9	± 26.9	± 10.2	± 10.5	± 214.2	± 223.9
SRP (μg.L^{-1})	12.6	16	18.8	48.9	-	23.4	99.6	23.4	96.3	10.6	1.5	15.4	17.8	18.7	5.9
	± 15.9	± 15.8	± 18.0	± 25.2		± 32.5	± 131.7	± 31.1	± 70.1	± 18.3		± 35.1	± 35.4	± 15.3	± 8.8
TP (μg.L^{-1})	197.3	444.8	217.1	226.3	-	61.1	259	325.8	406.4	447.9	40	121.4	129.4	183.5	414.6
	± 284.5	± 171.7	± 76.2	± 36.4		± 52.8	± 172.5	± 192.9	± 268.2	± 360.4	± 49.5	± 57.2	± 61.6	± 201.9	± 157.6

Legend: Z_{eu} = euphotic zone; $N\text{-}NO_3$ = nitrate; $N\text{-}NO_2$ = nitrite; $N\text{-}NH_4$ = ammonium; SRP = soluble reactive phosphorus; TP = Total phosphoru.

Table 2. Phytoplankton functional groups and respective species in three shallow aquatic ecosystems of semiarid region, Brazil.

Functional Group	Soledade reservoir	Taperoá reservoir	Panati lagoon
B	*Aulacoseira italica* (Ehrenberg) Simonsen	*Aulacoseira italica* (Ehrenberg) Simonsen	*Aulacoseira italica* (Ehrenberg) Simonsen
C	*Cyclotella meneghiniana* Kützing	*Cyclotella meneghiniana* Kützing	*Cyclotella meneghiniana* Kützing
D	*Nitzschia longissima* (Brébisson) Ralfs, *Nitzschia incurva* var. *lorenziana* R. Ross, *N. closterium* (Ehrenberg) W.Smith	*Nitzschia* sp., *N. contorta* C.Mereschkowsky, *N. longissima* (Brébisson) Ralfs, *N. obtusa* W.Smith, *Tryblionella apiculata* W.Gregory	
F	*Mucidosphaerium pulchellum* [(H.C.Wood) C.Bock, Proschold & Krienitz], *Oocystis* sp., *O. borgei* J.W.Snow, *O. lacustris* Chodat	*Botryococcus braunii* Kützing, *Mucidosphaerium pulchellum* [(H.C.Wood) C.Bock, Proschold & Krienitz], *Micractinium pusillum* Fresenius, *Oocystis borgei* J.W.Snow, *O. lacustris* Chodat	*Botryococcus braunii* Kützing, *Mucidosphaerium pulchellum* [(H.C.Wood) C.Bock, Proschold & Krienitz], *Oocystis borgei* J.W.Snow, *Kirchneriella obesa* (West) West & G.S.West, *Raphidocelis danubiana* (Hindák) Marvan, Komárek & Comas
H1	*Anabaenopsis circularis* (G.S.West) Woloszynska & V.V.Miller, *A. elenkinii* V.V.Miller, *Aphanizomenon gracile* Lemmermann	*Anabaena* sp., *A. sphaerica* Bornet & Flahault, *Aphanizomenon gracile* Lemmermann, *Dolichospermum circinale* (Rabenhorst ex Bornet & Flahault) P.Wacklin, L.Hoffmann & J.Komárek, *D. solitarium* (Klebahn) Wacklin, L.Hoffmann & Komárek	
J	*Monactinus simplex* (Meyen) Corda, *Scenedesmus acuminatus* (Lagerheim) Chodat, *S. quadricauda* (Turpin) Brébisson, *Coelastrum microporum* Nägeli, *Hariotina reticulata* P.A. Dangeard	*Coelastrum microporum* Nägeli, *Hariotina reticulata* P.A. Dangeard	*Coelastrum microporum* Nägeli, *Hariotina reticulata* P.A.Dangeard, *Willea crucífera* (Wolle) D.M.John, M.J.Wynne & P.M.Tsarenko, *Crucigenia fenestrata, C. tetrapedia, Monactinus simplex, Stauridium tetras, Scenedesmus quadricauda* (Turpin) Brébisson, *Desmodesmus denticulatus* var. *linearis, D. bicaudatus, Tetraedron trigonum, T. victorae, Tetrastrum elegans, Pediastrum duplex, P. biwae, P. ovatum, Parapediastrum biradiatum*
K	*Aphanocapsa delicatissima* West & G.S.West	*Aphanocapsa delicatissima* West & G.S.West	
L_O	*Coelosphaerium* sp., *Merismopedia minima* G.Beck, *M. tenuissima* Lemmermann, *Parvodinium umbonatum* (F.Stein) Carty		*Parvodinium umbonatum, Peridinium volzii, Chroococcus sp., Chroococcus turgidus (Kützing) Nägeli, Radiocystis fernandoi*
L_M	*Coelomoron tropicale* P.A.C.Senna, A.C.Peres & Komárek		*Coelomorom tropicale*
M	*Microcystis aeruginosa* (Kützing) Kützing, *Sphaerocavum brasiliense De Azevedo & C.L.Sant' Anna*	*Microcystis aeruginosa* (Kützing) Kützing	*Microcystis aeruginosa* (Kützing) Kützing, *Sphaerocavum brasiliense De Azevedo & C.L.Sant' Anna*
MP	*Eunotia* sp., *Oscillatoria* sp., *O. formosa* Bory ex Gomont, *O. tenuis* C. Agardh ex Gomont	*Amphora copulata* (Kützing) Schoeman & R.E.M. Archibald, *Cocconeis placentula* Ehrenberg, *Cymbopleura* sp., *Eunotia pectinalis* (Kützing) Rabenhorst, *Gomphonema* sp., *G. parvulum* (Kützing) Kützing, *Lemnicola exigua* (Grunow) Kulikovskiy, Witkowski & Plinski in Plinski & Witkowski, *Navicula* sp., *Navicula* sp. 2, *Oscillatoria* sp., *O. tenuis* C.Agardh ex Gomont, *Pinnularia* sp., *P. viridis* (Nitzsch) Ehrenberg, *Stauroneis* sp., *Surirella robusta* Ehrenberg, *Ulnaria ulna* (Kützing) Compère	*Amphora* sp., *A. ovalis* (Kützing) Kützing, *A. copulata* (Kützing) Schoeman & R.E.M. Archibald, *Desmidium* sp., *Gomphonema parvulum* (Kützing) Kützing, *Navicula* sp., *Navicula* sp. 2, *Oscillatoria* sp. 2, *O. tenuis* C.Agardh ex Gomont, *Pinullaria* sp., *Stauroneis* sp., *Ulnaria ulna* (Kützing) Compère
N			*Cosmarium* sp. 2, *C. botritys* Meneghini ex Ralfs, *C. laeve* Rabenhorst, *C. reniforme* (Ralfs) W.Archer, *C. pseudoretusum* F.Ducellier, *Euastrum* sp., *E. amoenum* F.Gay, *E. evolutum* (Nordstedt) West & G.S.West, *Octacanthium* sp., *Micrasterias radians* W.B.Turner

Table 2. Continued...

Functional Group	Soledade reservoir	Taperoá reservoir	Panati lagoon
P	*Aulacoseira granulata* (Ehrenberg) Simonsen, *Closterium* sp., *C. parvulum* Nägeli, *Fragilaria capucina* Desmazières	*Aulacoseira granulata* (Ehrenberg) Simonsen, *Closterium* sp., *Paralia sulcata*	*Aulacoseira granulata* (Ehrenberg) Simonsen, *Closterium* sp., *Fragilaria capucina* Desmazières
S1	*Planktothrix agardhii* (Gomont) Anagnostidis & Komárek, *Pseudanabaena limnetica* (Lemmermann) Komárek, *P. moniliformis* Komárek & Kling, *Geitlerinema* sp., *Romeria* sp.	*Planktothrix agardhii* (Gomont) Anagnostidis & Komárek, *Pseudoanabaena limnetica* (Lemmermann) Komárek	*Pseudanabaena* sp.
S2	*Spirulina laxissima* G.S.West	*Glaucospira laxissima*	
S_N	*Raphidiopsis raciborskii* (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique & Salerno, *R. mediterranea* Skuja	*Raphidiopsis raciborskii* (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique & Salerno, *R. mediterranea* Skuja	*Raphidiopsis raciborskii* (Woloszynska) Aguilera, Berrendero Gómez, Kastovsky, Echenique & Salerno
T			*Mougeotia* sp.
T_D	*Oedogonium* sp.		*Spirogyra* sp.
W1	*Euglena* sp., *E caudata* E.F.W.Hübner, *Euglena formis proxima* (P.A.Dangeard) M.S.Bennett & Triemer, *Lepocinclis* sp., *L. oxyuris* (Schmarda) B.Marin & Melkonian, *L. salina* F.E.Fritsch, *L. salina* var. *salina* F.E.Fritsch	*Euglenaria caudata* (E.F.W.Hübner) Karnowska-Ishikawa, Linton & Kwiatowski, *Euglena formis proxima* (P.A.Dangeard) M.S.Bennett & Triemer in Bennett & Triemer, *Lepocinclis oxyuris* (Schmarda) B.Marin & Melkonian, *L. fusiformis, L. salina* F.E.Fritsch, *L. salina* var. *salina* F.E.Fritsch, *Phacus contortus* Bourrelly, *P. orbicularis* K.Hübner	*Cryptoglena agilis* Ehrenberg, *Euglena archaeoplastidiata* Chadefaud, *E. gaumei* P.Allorge & M.Lefèvre, *Euglenaria caudata* E.F.W.Hübner, *Lepocinclis acus* (O.F.Müller) B.Marin & Melkonian, *Lepocinclis* sp., *L. salina* F.E.Fritsch
W2	*Trachelomonas volvocina* (Ehrenberg) Ehrenberg, *T. volvocinopsis* Svirenko, *Trachelomonas* sp.1, *Trachelomonas* sp.3, *Trachelomonas* sp.6	*Trachelomonas oblonga* Lemmermann, *T. oblonga* var. *pulcherrima* Playfair, *T. sculpta* Balech, *T. volvocina* var. *volvocina* Drezepolski, *T. volvocinopsis* Swirenko var. *volvocinopsis*	*Strombomonas* sp., *S. fluviatilis* (Lemmermann) Deflandre, *Trachelomonas oblonga* Lemmermann, *T.volvocina* (Ehrenberg) Ehernberg var. *volvocina, T. volvocinopsis* Swirenko *var. volvocinopsis*
X_1	*Schroederia setigera* (Schröder) Lemmermann	*Chlorococcum* sp., *Schroederia setigera* (Schröder) Lemmermann, *S. indica* Philipose	*Monoraphidium* sp., *M. arcuatum* (Korshikov) Hindák, *M. contortum* (Thuret) Komárková-Legnerová

2008 [mainly *Monactinus simplex* (Meyen) Corda] and September and December 2009 [mostly *Hariotina reticulata* P.A.Dangeard]. Several species of euglenophycean belonging to groups $\mathbf{W_1}$ and $\mathbf{W_2}$ presented great abundance throughout the study period. Among colonial cyanobacterias, the two functional groups $\mathbf{L_O}$ [mainly *Chroococcus turgidus* (Kützing) Nägeli] and **M** (mainly *Sphaerocavum brasiliense* De Azevedo & C.L.Sant'Anna) were only abundant in August 2010. The functional group **MP** (mainly *Stauroneis* sp.) stood out in some months, such as between July 2006 and June 2007 and June 2008 (Figure 5c).

3.3. RDA of phytoplankton functional groups and environmental factors

The RDA (Figure 6) of the 21 functional groups and 8 environmental variables explained 24.4% of total data variance in the first two axes (axis 1: 17.9%, eigenvalue: 1.032; axis 2: 6.5%, eigenvalue: 0.374). The results generated in the ordination were significant according to the permutation test (ANOVA: F = 3.44, p = 0.001). The axis 1 ordered on the positive side most of the Soledade reservoir sampling sites associated mainly with high values of pH (r = 0.60), while most of the sampling sites of the Taperoá reservoir and Panati lagoon were ordered on the negative side associated with high values of Z_{eu} (r = -0.47) and NO_3 (r = -0.21). On the positive side of axis 2 were ordered most of the Soledade sampling sites and all Taperoá reservoir sites associated with high concentrations of NO_2 (r = 0.36) and NH_4 (r = 0.29), while most of the Panati lagoon sites were sorted on the opposite side associated with lower values of the variables mentioned above. The condition of higher pH and lower values of Zeu and NO_3 favored higher biomass of the functional groups **M**, $\mathbf{H_1}$, $\mathbf{S_N}$, $\mathbf{S_2}$, $\mathbf{L_O}$, **F**, $\mathbf{L_M}$ and **K** mainly in Soledade reservoir. The FGs $\mathbf{W_1}$, **J**, **MP** and $\mathbf{W_2}$ showed greater development under conditions with lower values of inorganic nutrients and Zeu, especially in some months in the Panati lagoon.

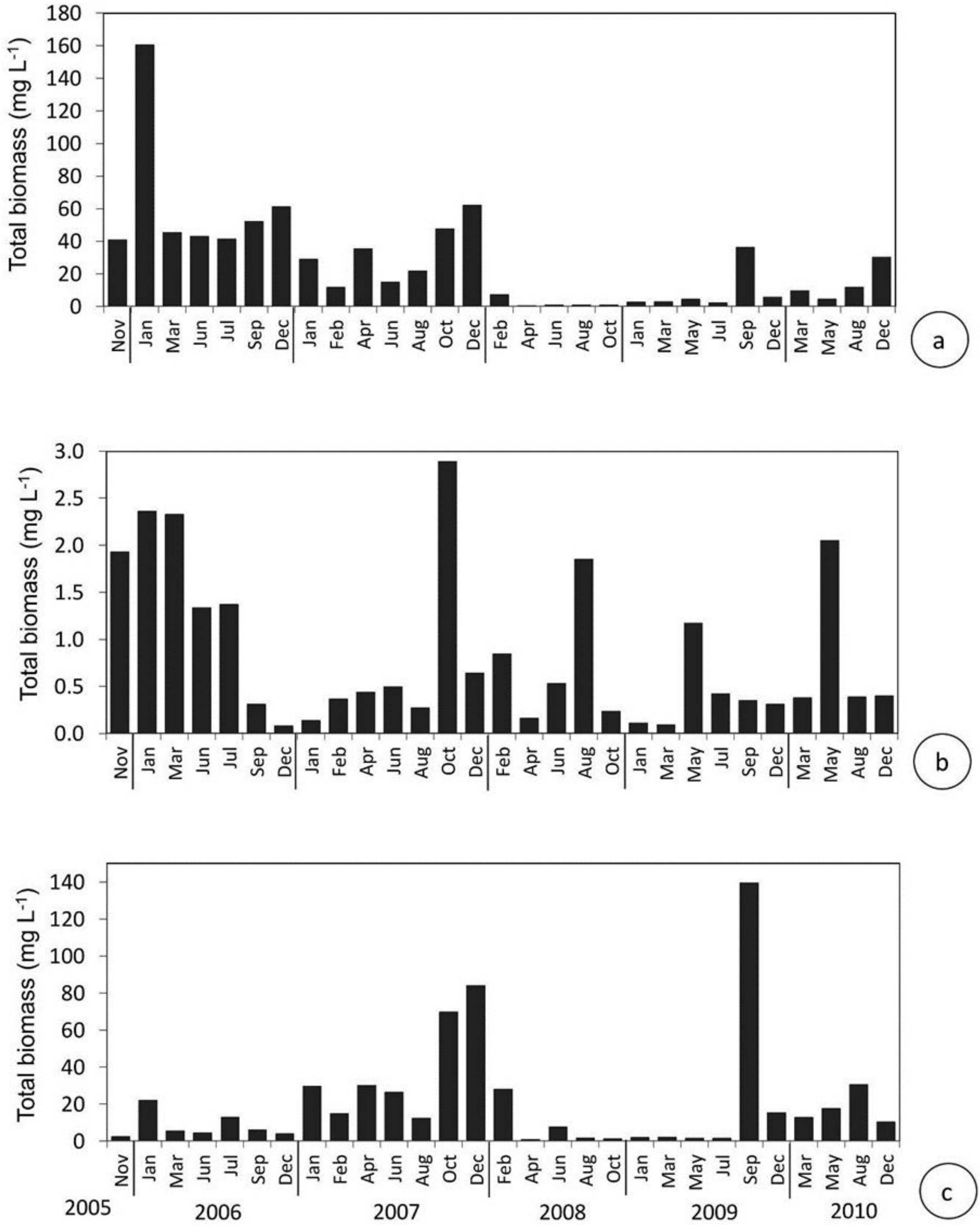

Figure 4. Absolute biomass of the phytoplankton community in Soledade (a) and Taperoá (b) reservoirs and Panati lagoon (c) from November 2015 to December 2010.

3.4. Assemblage index (Q) in the natural lagoon and reservoirs

Table 3 shows the factor F weight established for each FG registered in the three aquatic ecosystems. During the five study years, the ecological status of Soledade reservoir was classified as bad (0.2-1.0) during most study months (Mar-Sep/2006, Jan/2007, Aug/2008, Mar-Jul/2009, Dec/2009 and May/2010) (Figure 7). The high contribution of the functional groups $\mathbf{S_N}$, **M**, $\mathbf{H_1}$ and $\mathbf{S_1}$ in these months coincided with reduced water quality- Good conditions (3.1-3.8) were only identified in a few months.

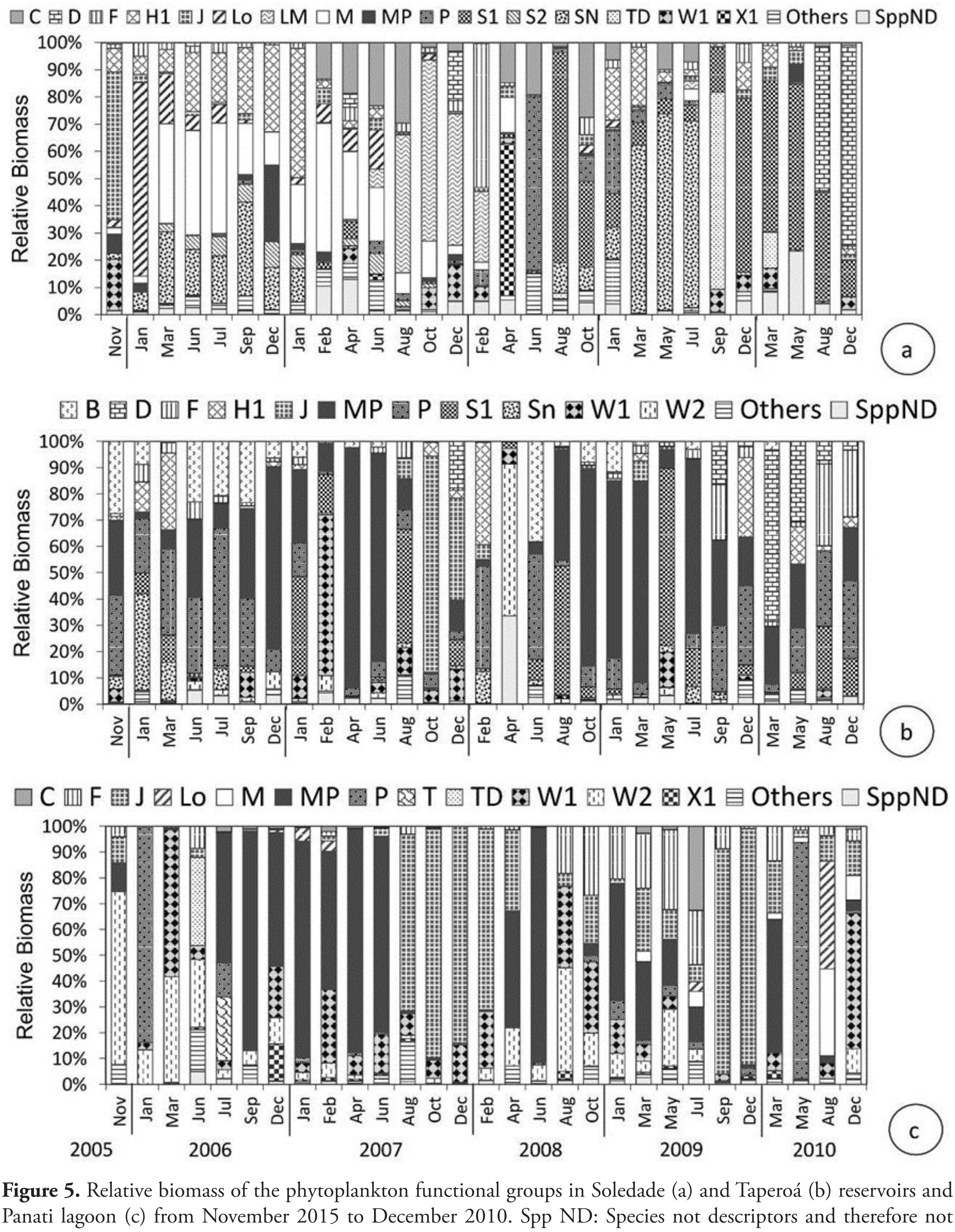

Figure 5. Relative biomass of the phytoplankton functional groups in Soledade (a) and Taperoá (b) reservoirs and Panati lagoon (c) from November 2015 to December 2010. Spp ND: Species not descriptors and therefore not grouped into functional groups.

The ecological conditions of the Taperoá reservoir ranged from bad (0.7) to good (2.1-3.0). Bad or tolerable classifications coincided with the period of highest cyanobacteria biomass belonging to groups $\mathbf{H_1}$, $\mathbf{S_N}$ and/or $\mathbf{S_1}$ and euglenophyceans of the functional group $\mathbf{W_1}$. The classification of the Q index was good in most months, especially during those when the functional groups **B**, **D** and **MP** (diatoms) highly contributed to biomass (Figure 7).

The Panati lagoon presented the highest values of the index (Figure 7), with condition classified as good to excellent in those months with high contribution from the groups **MP**, **F** and **J**. However, in the first and last months of the study

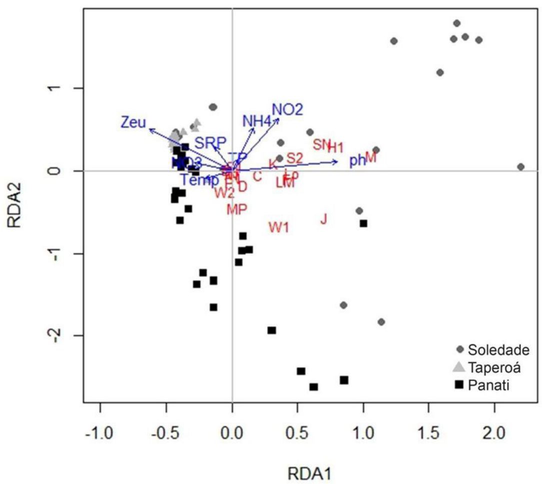

Figure 6. Ordination of the Redundancy Analysis (RDA) axes applied to the eight abiotic variables and 21 biotic variables (functional groups) of the Soledade and Taperoá reservoirs and Panati lagoon from November 2005 to December 2010. Sampling sites with missing data (nutrients - Jul/2009 to Dec/2010) in the Soledade reservoir were removed from the analysis. Legend: Temp (water temperature), Zeu (euphotic zone), NO3 (nitrate), NO2 (nitrite), NH4 (ammonium), SRP (soluble reactive phosphorus), TP (total phosphorus), ph (pH).

Table 3. Factor F weight to phytoplankton functional groups in three shallow aquatic ecosystems of semiarid region, Brazil.

Functional Groups	Factor F		
	Soledade reservoir	Taperoá reservoir	Panati lagoon
B	3.5	3.5	3
C	3.5	3.5	3
D	3	3	-
F	3	3	4
H1	0	0	-
J	2.5	2.5	3.5
K	3	3	-
L_O	4	-	4
L_M	1	-	0
M	0	0	0
MP	4	4	5
N	-	-	5
P	3	3	2
S1	0	0	0
S2	2	2	-
S_N	0	0	0
T	-	-	5
T_D	5	-	5
W1	2	2	3
W2	1	1	1
X1	3	3	3

period, values recorded in the tolerable to medium range were associated with the high contribution of **W_1, W2**, **P** and **M** groups.

4. Discussion

Our results showed that the distribution of the phytoplankton functional groups between ecosystems reflected the high nutrient concentrations, alkaline pH, underwater light climate, as well as differences in the typologies and regime of the ecosystems, with the highest dominance of cyanobacteria in the reservoirs. Despite the same climate conditions, the reservoirs presented high concentrations of nutrients and higher harmful cyanobacteria contribution (**M, S1** and **S_N**), while the Panati, a natural and temporary lagoon, presented lower contribution of cyanobacteria.

According to tendencies revealed by RDA, the limnological differences between ecosystems were more important than seasonal changes. Additionally, the temporal fluctuations showed relevance, mainly those associated with the rainfall contribution, low and irregular over interannual scale, indicating the importance of the stochastic factors on the functional groups structure in semiarid reservoirs. In semiarid regions, the high water abstraction and extreme fluctuations of water volume contribute to the water quality decrease during the end of the rain and prolonged droughts (Braga et al., 2015).

Among the main driving factors, pH, nutrients and light availability influenced the distribution of the sampling units. Therefore, since temporal gradient was less important, the differences between ecosystems may have helped the cyanobacteria to maintain and persist in Soledade and Taperoá (e. g. **H1**, **S_N**, **S_1**, **M**) and the non-motile green algae, euglenoids and diatoms in Panati (e. g. **F**, **J**, **W_1**, **W_2**, **MP**). Generally, these last FGs can be found in shallow and temporary lakes, with moderate nutrient concentrations (meso-eutrophic ponds) and waters rich in organic matter (Padisák et al., 2009). On the other hand, Taperoá presented high diatoms biomass, associated with functional groups typical from turbid and meso-eutrophic waters (e.g., **B**, **D** and **P**) (Padisák et al., 2009).

Warmer climate and water level reduction in semiarid reservoirs can induce high values of phytoplankton biomass when compared to reservoirs in subtropical regions, promoting optimal conditions for the development of cyanobacteria, such as high water temperature, high nutrient concentrations and lower transparency (Brasil et al., 2016; Costa et al., 2016; Barros et al., 2019),

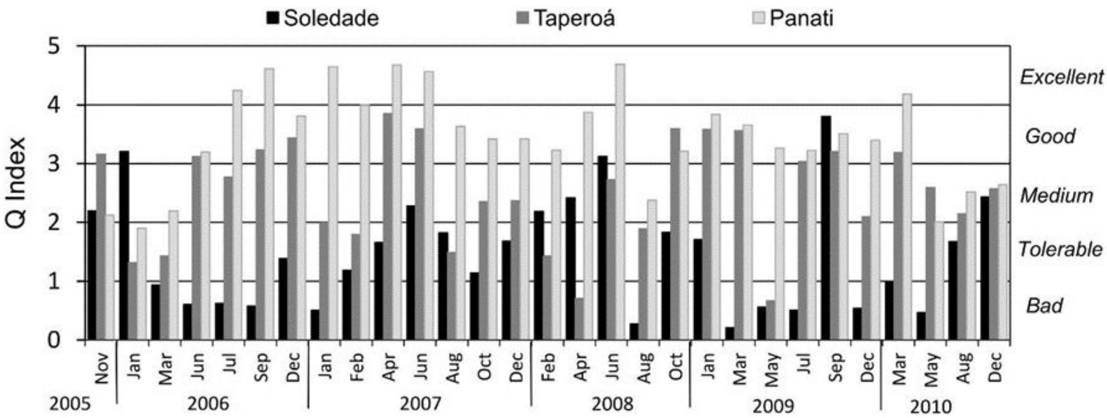

Figure 7. Ecological status of the Soledade and Taperoá reservoirs and Panati lagoon through the Q index of phytoplankton functional groups (November 2005 to December 2010).

which are the environmental conditions found in Soledade. Hydrologic changes associated with global warming or human activities can also promote the geographic expansion of toxic cyanobacteria, as those species have higher replication rates at high temperatures (e.g., Paerl & Paul, 2012) and in nutrient over-enriched conditions.

The occurrence of extreme rainfall in April 2008 promoted the increase of water volume in Soledade and Taperoá and changes in the phytoplankton biomass, directly influencing the decrease of cyanobacteria in June 2008. The reduction of cyanobacteria contribution is a common pattern within semiarid reservoirs after the rainy events or at the end of rain period (Brasil et al., 2016), when the increased of volume and overflow promote the replacement of the cyanobacteria by Chlorophyta and other groups (e.g. Chellappa et al., 2009; Lins et al., 2016).

The several conditions identified with the increases of cyanobacterial biomass have been associated with the consequences of water level reductions (Bakker & Hilt, 2016; Yang et al., 2016), generally associated with the prolonged and extreme droughts in arid and semiarid zones (Brasil et al., 2016; Costa et al., 2016). In this way, besides the reduction of water levels due to global warming, water catchment demand for multiple uses may also induce favorable conditions for cyanobacteria development.

Temporary lagoons are very dynamic ecosystems, with a considerable water level fluctuation completely dependent on the local rainfall regime and frequently drying partially or completely over the year (Calhoun et al., 2017). In these ecosystems, the flora and fauna are influenced by the water regime (Sandi et al., 2020) and hydroperiod length (Vanschoenwinkel et al., 2009). In the Panati lagoon, the role of macrophyte cover as a refuge and substrate has been associated with the higher diversity of macroinvertebrates, for instance (Souza & Abílio, 2006). Last years, partial or complete desiccations was observed in Panati (Souza & Abílio, 2006), which may have generated a natural control mechanism acting on the reduction of cyanobacteria blooms and on the water quality improvement (Teferi et al., 2014). Over the study period the desiccation in Panati was only partial, reducing drastically the water level.

In general, the bad and tolerable conditions showed by the Q index in Soledade and Taperoá reservoirs emphasized the temporal persistence of bloom-forming cyanobacteria such as *Microcystis aeruginosa* (**M**), *Raphidiopsis raciborskii* ($\mathbf{S_N}$), *Anabaenopsis elenkinii* V.V.Miller ($\mathbf{H_1}$) and *Planktothrix agardhii* ($\mathbf{S_1}$). Among the species in these groups, *Raphidiopsis raciborskii* is very often cited as one of the causes of the blooms in the Northeast region (Bouvy et al., 2003; Costa et al., 2006; Dantas et al., 2008; Brasil et al., 2016), associated with adaptation to high fluctuation in nutrient availability (Bormans et al., 2005), low light intensity and eutrophic waters (Stüken et al., 2006).

In summary, the composition of phytoplankton functional groups directly influenced the Q index results, with the highest values in Panati, indicating the role of drying on the water quality. Therefore, our results showed that the total or partial drying may have been a natural control of the cyanobacterial biomass present in natural temporary lagoons. In relation to the Soledade reservoir, the increase of the volume and consequently overflow was not sufficient to breakdown the stability present in them and, consequently, the harmful cyanobacterial functional groups contribution was not reduced, showing mostly bad to tolerable conditions. In addition, the Q index was a good tool to assess the water quality and ecological status in aquatic ecosystems from the Brazilian semiarid region, reflecting the influence of natural control mechanisms on the harmful cyanobacteria blooms in temporary ecosystems.

Acknowledgements

The authors thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the financial support received through the PELD-CAATINGA (The Long-Term Ecological Research Program - PELD, in Portuguese).

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Received: 23 October 2020
Accepted: 09 September 2021

Associate Editor: André Andrian Padial.