REVISTA DE
Biología Tropical

Phytoplankton functional groups in a tropical reservoir in the Brazilian semiarid region

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Received 05-VII-2016. Corrected 26-IV-2017. Accepted 30-V-2017.

Abstract: Phytoplankton functional groups structure and species abundance vary according to environmental conditions. The present study investigated the natural and anthropogenic stressors that affect phytoplankton functional group biomass in a Brazilian semiarid region reservoir (Argemiro de Figueiredo reservoir). Sampling occurred between August 2007 and July 2009 on a bi-monthly basis for the first year, and in a monthly basis for the last two years. There were three collection points (PC: river confluence; PNC: near the cages; PD: dam site). The water environment analysis of abiotic variables included: temperature, transparency, coefficient of vertical light attenuation, dissolved oxygen, pH, electrical conductivity, alkalinity, dissolved inorganic nitrogen, and reactive soluble phosphorus. Phytoplankton samples were collected into a Van Dorn bottle, and were then preserved in acetic lugol and were quantified using an inverted microscope to determine phytoplankton density and biomass; the identified species were assembled in functional groups. The data were explored by canonical correspondence analysis. Individual analyses were made to test the temporal and spatial variability of the data and the factors that interfered most with the biotic and abiotic variables. Functional groups S1, SN, and K, consisting of filamentous *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek, *Cylindrospermopsis raciborskii* (Woloszynska) Seenaya & Subba Raju, and the coccoid *Aphanocapsa incerta* (Lemmermann) Cronberg & Komárek, respectively, dominated the dry months when the water was warm, turbid, and alkaline. The overflow reservoir served as a natural disturbance reducing the phytoplankton biomass to less than 50 % and the dominance of cyanobacteria, promoting the domain of functional groups F, M, MP, Lo, and X2. The nutrient inputs from intensive fish farming, associated with a low local depth (Z_{max} = 7.7 m) close to the cages (PNC), resulted in a significant human disturbance that increased the prevalence of functional groups S1, SN, and K, which are composed primarily of cyanobacteria. We concluded that, in reservoirs, overflow events are natural disturbances that have the ability to reduce phytoplankton biomass and alter the structure of local communities, and that intensive fish farming is an anthropogenic disturbance that increases the availability of nutrients and stimulates an increase in biomass of the functional groups that include cyanobacteria. Furthermore, the functional groups of phytoplankton were reliable control of environmental conditions in the reservoirs of tropical semiarid regions. Rev. Biol. Trop. 65 (3): 1129-1141. Epub 2017 September 01.

Key words: phytoplankton, functional groups, climatic conditions, biomass stability, reservoir, semiarid region, natural and anthropogenic stressors.

The semiarid region of Brazil experiences extreme seasonal variations in rainfall. Precipitation is concentrated in a few months of the year and is followed by a long dry season with significant inter-annual variability. The characteristics of semiarid Northeastern Brazil and high environmental temperatures there create water deficits for at least 70 % of the year.

Cycles of both drought and extreme rainfall occur at intervals ranging from a few years to decades. Therefore this environment is vulnerable and its climate is unstable (Marengo, Alves, Beserra, & Lacerda, 2011). These conditions are conducive to high evaporation rates and long reservoir water residence times, and significantly influence lacustrine phytoplankton organization (Bouvy, Falcão, Marinho, Pagano, & Moura, 2000), they favor cyanobacterial blooms in dry periods.

Natural or anthropogenic events that alter the hydrodynamic and limnological characteristics of the environment can adversely affect reservoirs (Straskraba, Tundisi, & Duncan, 1993). Different levels of disturbance affect community organization in various ways (Lopes, Ferragut, & Bicudo, 2009) and may interrupt, postpone, or redirect seasonal phytoplankton successions (Znachor, Zapomělová, Řeháková, Nedoma, & Šimek, 2008). Abrupt changes in species composition can occur that interfere with internally driven self-organization and ecological equilibrium processes (Reynolds, Padisák, & Sommer, 1993). There have been numerous studies on the environmental impact of tropical reservoirs on phytoplankton. Nevertheless, they usually focused on anthropogenic disturbances; few studies examined the impacts associated with natural disturbances (Chellappa, Chellappa, Câmara, Rocha, & Chellappa, 2009a; Câmara, Rocha, Pessoa, Chellappa, & Chellappa, 2015).

Reservoirs in the semiarid region of Brazil are usually very hydrologically stable (Bouvy et al., 2000). This factor is critical for sustaining the long-term dominance of certain phytoplankton species (Huszar, Silva, Marinho, Domingos, & Sant'Anna, 2000). Cyanobacterial species forming perennial blooms have been identified in eutrophic reservoirs in the semiarid region of Brazil (Chellappa, Chellappa, & Chellappa, 2008; Dantas, Moura, & Bittencourt-Oliveira, 2011) and in many other places worldwide (Naselli-Flores, Barone, Chorus, & Kurmayer, 2007; Dejenie et al., 2008; Douma et al., 2010). Factors that contribute to the distribution and stability patterns of phytoplankton in these reservoirs include trophic states (Barone & Naselli-Flores, 1994; Naselli-Flores, 2013), multidimensional environmental gradients (Fabbro & Duivenvoorden, 2000), and survival strategies (Reynolds, 1998).

The present study examined the environmental variables having the greatest influence on the seasonal and spatial dynamics of the phytoplankton communities in a eutrophic reservoir in the semiarid region of Brazil, the Argemiro de Figueiredo reservoir. According to Lins, Barbosa, Minillo and Ceballos (2016), perennial blooms of toxic cyanobacteria are common in this reservoir, particularly during the dry months of the season in the region. Thus, we investigated the roles of natural and anthropogenic disturbances that alter phytoplankton biomass stability. Two questions were raised: (i) Is reservoir overflow a natural disturbance that can disrupt or alter phytoplankton biomass? (ii) Do the nutrients derived from pisciculture in the reservoir cause an anthropogenic disturbance that increases the biomass of cyanobacterial phytoplankton functional groups? To answer these questions, we analyzed the reservoir's phytoplankton population using the functional group. This approach has been widely employed in ecological studies and is an effective tool for explaining community structures and their responses to alterations in environmental conditions (Kruk, Mazzeo, Lacerot, & Reynolds, 2002; Kruk et al, 2011; Brasil & Huszar, 2011; Reynolds, 2014; Török et al, 2016).

MATERIALS AND METHODS

Description of the study area: The present study was undertaken at the Argemiro de Figueiredo reservoir (7° 36' 51" S - 35 40' 31" W) in the median portion of the Paraiba River basin, which is the largest in Paraiba State, Brazil. The reservoir has a surface area of 1 725 ha, a potential volume of 2.53×10^8 m^3, a maximum depth of 39 m, and a hydraulic residence time of 146 days. The regional climate is hot semiarid (type BSh) with a high evaporation rate (Silva, Sousa, Kayano, & Araujo, 2008). The average annual rainfall varies from 600 - 1 100 mm with very irregular monthly and annual regimes. There are marked rainy and dry seasons (Governo do Estado da Paraiba, 2007). The reservoir was constructed in 2001 and is used, among other purposes, for supplying water to approximately 450 000 regional inhabitants and for the production of Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) in net cages. The latter activity began in December 2006. Before the net cages were deployed, however, the reservoir water was eutrophic and experienced intense cyanobacterial blooms (> 240 000 ind. mL^{-1}). *Microcystis aeruginosa* (Kützing) Kützing and *Cylindrospermopsis raciborskii* predominated, among other potentially toxic species (Barbosa & Mendes, 2005).

Sampling and analysis methods: Samples were collected between August 2007 and July 2009, bimonthly for the first year, and at monthly intervals thereafter. Three sampling points were considered: the confluence of two feeder rivers (PC), near the net cages (PNC), and in the dam zone (PD); while samples were taken in the euphotic (Z_{eup}) and aphotic zones (Z_{aph}). Water transparency was measured using a Secchi disk, and the euphotic zone (Z_{eup}) was calculated as 3.0 times the Secchi disk depth (Cole, 1994). The vertical light attenuation coefficient (K_o) was calculated according to Poole and Atkins (1929). Rainfall and monthly reservoir volume data were obtained from the Executive Agency of Water Control of Paraiba State. Water temperatures, pH, and electrical conductivity were measured *in situ* using an INCOTERM model 2309 thermometer, a Tecnal digital pH meter, and a Lutron model 4303 conductivity meter, respectively. Alkalinity was determined as described by Mackereth, Heron and Talling (1978).

Samples for the analyses of nutrients, dissolved oxygen, alkalinity, and phytoplankton community composition were taken at two depths using a Van Dorn-type collector (5 liters). The samples used for the identification and quantification of phytoplankton were fixed in formaldehyde (4 %) and Lugol's solution, respectively. The dissolved oxygen content was determined following the method of Golterman, Clymo and Ohnstad (1978). Soluble reactive phosphorus (SRP) was determined using the ammonium molybdate methodology (APHA, 2005). Dissolved inorganic nitrogen (DIN) was calculated from the sums of the ammonia, nitrite, and nitrate concentrations obtained using the phenol, *diazotization* of *sulfanilamide*-NED, and cadmium reduction techniques respectively (APHA, 2005). The DIN:SRP molar ratio was used to evaluate the possibility of phytoplankton growth restrictions due to nitrogen or phosphorus limitations, where DIN:SRP < 13 indicates limiting nitrogen, DIN:SRP > 50 indicates limiting phosphorus, and 13 < DIN:SRP < 50 indicates that neither of these nutrients is limiting (Morris & Lewis, 1988; Kosten et al., 2009). The Carlson index of Tropic States, adapted by Toledo, Talarico, Chinez and Agudo (1983) for tropical regions, was used for trophic characterization. The quantitative analyses of the phytoplankton followed the method of Utermöhl (1958). At least 100 individuals from the most frequently encountered species were enumerated (error < 20 %, p < 0.05) and this number increased during bloom periods, when were counted in each sample, at least 400 individuals of the dominant species (error < 10 %, p < 0.05) (Lund, Kipling, & Le Cren, 1958).

The phytoplankton biovolume ($mm^3.L^{-1}$) was estimated on the basis of a geometrical formula (Hillebrand, Dürselen, Kirschtel, Pollingher, & Zohary, 1999; Sun & Liu, 2003) using an average of 20-30 individuals and was expressed in fresh weight units, where 1 $mm^3.\ L^{-1} = 1$ mg. L^{-1} (Wetzel & Likens, 2000). All phytoplankton species were assembled into functional groups following the criteria established in the study by Reynolds, Huszar, Kruk, Naselli-Flores and Melo (2002) and reviewed by Padisák, Crossetti and Naselli-Flores (2009).

A Canonical Correspondence Analysis (CCA) was performed using Canoco

4.5 forward selection, based on a biotic matrix (functional phytoplankton groups), and an abiotic matrix (Ter Braak & Smilauer, 2002). The significance of the environmental variables ($p < 0.05$) was determined using the Monte Carlo test with 999 unrestricted permutations. Individual analyses were made to test the temporal and spatial variability of the data and the factors that interfered most with the biotic and abiotic variables. These factors were analyzed using a generalized linear model (the covariance analysis module of Statistica 8.0) which incorporated the following components: collection points, water depth, rainfall, and presence or absence of overflow events.

RESULTS

Regional climatic conditions influenced reservoir volume and hydrodynamics, and, consequently, functional groups replacement and biomass. Two dry seasons with sparse rainfall as well as two rainy seasons were identified during the study period. During some of the rainy months, the accumulated water exceeded the reservoir capacity, resulting in overflow for 59 days during the first event (March-May 2008) and 114 days during the second (May-September 2009) (Fig. 1).

The reservoir water was warm (> 24.0 °C; N = 132), alkaline (> 36.0 mg $CaCO_3.L^{-1}$; N = 132), basic (minimum = 7.0; maximum = 10.0; N = 132), and high in electrical conductivity (> 357.3 $\mu S.cm^{-1}$; N = 132) (Table 1). Eutrophic conditions predominated with no significant seasonal variations. Reductions in pH values, electrical conductivity, alkalinity, and dissolved oxygen (DO) were only observed during periods of overflow. Significant spatial differences were noted for pH and DO. The highest values for both were measured near the net cages. pH and DO in the vertical profiles were highest in the euphotic zone, while alkalinity, SRP, and DIN were highest in the aphotic zone (Table 2).

Transparency values for both the dry and rainy seasons indicated that waters were turbid at all collection points and the euphotic zone was reduced (Table 1). A single period of relatively clear water occurred at the second overflow event (Transparency = 1.5 m and Z_{eup} = 4.4 m).

The total phytoplankton biomass varied between 0.01 $mm^3. L^{-1}$ and 28.42 $mm^3. L^{-1}$ (Table 1). The lowest values were recorded during overflow events in the rainy season. The dominance of cyanobacterial functional groups (> 90 % of the total biomass) occurred during the dry season and some rainy months (Fig. 2). The point the net cages (PNC) had the highest

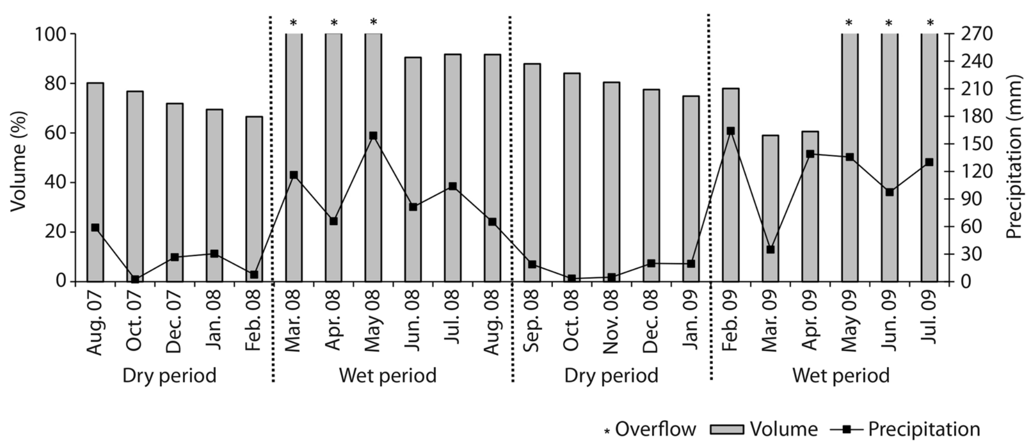

Fig. 1. Monthly rainfall and the volumes of accumulated water in the Argemiro de Figueiredo Reservoir in Paraiba State, Brazil, from August 2007 to July 2009.

TABLE 1

Minimum, averages ± Standard Deviation, and maximum values of abiotic variables, trophic state indices, and total biomass at the three collection points in the euphotic (*) and aphotic (**) zones of the Argemiro de Figueiredo reservoir (Brazil) from August/2007 to July/2009

	Confluence of the tributaries rivers (PC)			Near the fish net cages (PNC)			Near the dam (PD)		
	Min	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max
Secchi disk (m)	0.2	0.6±0.24	1.2	0.1	0.6±0.21	1.2	0.2	0.6±0.25	1.5
Z_{eup} (m)	0.5	1.8±0.73	3.6	0.4	1.7±0.64	3.6	0.5	1.8±0.74	4.4
K_o (m^{-1})	1.4	3.4±2.0	11.2	1.4	3.6±2.1	12.1	1.2	3.4±1.9	11.2
Depth (m)	21.0	29.7±4.81	36.7	4.5	6.21±1.01	7.7	22.1	31.4±5.13	39.0
Temperature (°C)	24.8*	29.0±1.61*	32.2*	24.3*	28.7±1.56*	30.5*	25.1*	28.2±1.62*	30.5*
	25.1**	27.8±1.22**	29.7**	24.2**	28.1±1.45**	30.0**	24.0**	27.2±1.61**	29.6**
Dissolved oxygen ($mg.L^{-1}$)	6.1*	11.7±4.1*	19.3*	6.4*	11.9±4.0*	21.3*	6.6*	11.1±3.6*	18.3*
	0.0**	5.0±4.2**	14.2**	2.8**	10.4.6**	23.2**	0.0**	4.1±4.1**	13.5**
pH	7.0*	8.6±0.74*	10.0*	7.3*	8.7±0.66*	9.5*	7.3*	8.6±0.62*	9.4*
	7.0**	7.8±0.57**	9.08**	7.0**	8.5±0.67**	9.2**	6.5**	7.7±0.65**	9.1**
Alkalinity ($mgCaCO_3.L^{-1}$)	37.0*	86.4±25.4*	127.0*	36.0*	87.0±25.9*	133.0*	38.0*	89.2±25.4*	132.0*
	47.0**	90.0±24.9**	144.0*	39.0**	88.6±25.3**	131.0**	40.0**	92.5±29.6**	163.0**
Conductivity ($\mu S.cm^{-1}$)	357.3*	821.3±276.3*	1 347.0*	414.7*	842.5±307.5*	1 506.0*	413.9*	826.6±274.9*	1325.0*
	389.4**	825.5±271.1**	1 294.0**	455.0**	859.0±369.8**	1 866.0**	392.7**	826.7±282.5**	1376.0**

	Confluence of the feeder rivers (PC)			Near the net cages (PNC)			Near the dam (PD)		
	Min	Mean±SD	Max	Min	Mean±SD	Max	Min	Mean±SD	Max
DIN ($\mu g.L^{-1}$)	20.5*	71.4±32.8*	163.6*	38.2*	89.3±40.7*	199.5*	17.9*	74.2±39.7*	178.2*
	31.9**	256.7±254.6**	867.3**	33.0**	98.0±63.3**	322.3**	22.2**	169.7±151.1**	696.6**
SRP ($\mu g.L^{-1}$)	10.1*	36.7±23.8*	100.3*	4.6*	37.6±24.12*	98.9*	0.29*	38.2±27.5*	90.3*
	11.7**	67.2±47.5**	186.0*	13.7**	44.1±29.9**	117.4**	16.0**	74.5±63.1**	253.1**
DIN:SRP	0.77*	1.9±1.3*	5.3**	0.29*	3.1±4.72*	22.8*	0.41*	8.8±31.8*	151.1*
	0.41**	3.5±3.9**	16.7*	0.55**	2.2±1.6**	7.3**	0.31**	2.3±1.7**	6.1**
Trophic state index	50.1	61.2±5.1	71.3	52.4	62.5±5.4	74.7	43.0	60.7±6,6	71.0
Total Biomass ($mm^3.L^{-1}$)	0.04*	4.05±6.6*	28.42*	0.07*	6.0±5.3*	22.32*	0.01*	4.37±5.6*	21.76*
	0.01**	0.56±0.60**	2.37**	0.01**	3.69±3.6**	15.53**	0.01**	1.15±2.4**	9.71**

Z_{eup}=euphotic zone, K_o=coefficient of vertical light attenuation, DIN= dissolved inorganic nitrogen, SRP= soluble reactive phosphorus, DIN: SRP= molar ratios of the dissolved organic nitrogen and reactive soluble phosphorus.

TABLE 2
Summary of the covariance analyses performed on the abiotic variables, phytoplankton species and functional groups related found in the Argemiro de Figueiredo Reservoir (Brazil) from August 2007 to July 2009

	Secchi	pH	EC	DO	Alkalinity	DIN	SRP	S1		M		P		SN	F	K	MP	H1	X2	Lo
								Plag	Pslin	Maer	Mcpr	Aulg	Closp	Crac	Botb	Apin	Ossp	Dcir	Chlsp	Pumb
Collection points	-	*	-	**	-	-	-	-	-	-	*	-	-	-	*	-	-	-	-	*
Depth	-	***	-	***	*	**	*	-	-	-	-	-	**	-	*	-	-	-	**	-
Precipitation	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	*	-	-
Overflow	***	**	***	***	***	-	-	*	-	-	**	-	*	-	-	-	-	-	**	-

Significant (* = p < 0.05, ** = p < 0.01, *** = p < 0.001); - = not significant (p > 0.10); EC = electrical conductivity, DO = dissolved oxygen, DIN = dissolved inorganic nitrogen, SRP = soluble reactive phosphorus, Plag = *Planktothrix agardhii*, Pslin = *Pseudanabaena limnetica*, Maer = *Microcystis aeruginosa*, Mcpr = *Microcystis protocystis*, Aulg = *Aulacoseira granulata*, Closp = *Closterium* sp., Crac = *Cylindrospermopsis raciborskii*, Botb = *Botryococcus braunii*, Apin = *Aphanocapsa incerta*, Ossp = *Oscillatoria* sp., Dcir = *Dolichospermum circinalis*, Chlsp = *Chlamydomonas* sp., Pumb = *Peridinium umbonatum*.

total biomass in both the euphotic (6.00 ± 5.3 mm^3. L^{-1}) and aphotic (3.69 ± 3.6 mm^3. L^{-1}) zones. This portion of the reservoir was also the shallowest (Z_{max} = 7.7 meters) (Fig. 2).

The thirteen dominant cyanobacterial species were arranged in functional groups S1, K, M, SN, H1, F, MP, P, Lo, and X2, which corresponded to the groups described by Reynolds et al. (2002). Groups S1, SN, and K consisted mainly of *Planktothrix agardhii*, *C. raciborskii,* and *Aphanocapsa incerta,* respectively. They predominated during the dry months in the warmest waters with high turbidity and alkalinity. Group P was represented by *Aulacoseira granulata* (Ehrenberg) Simonsen and *Closterium* sp. It predominated during the rainy months when the waters were coldest but there were no overflow events. Functional groups F, M, MP, Lo, and X2 occurred principally during rainy months marked by overflow events. They included the colonial species *Botryococcus braunii* Kützing*, M. aeruginosa*, and *Microcystis protocystis* Crow, the filamentous species *Oscillatoria* sp., and the unicellular flagellates *Peridinium umbonatum* Stein and *Chlamydomonas* sp., respectively. Group H1, with *Dolichospermum circinalis* (Ralfs ex Bornet & Flahault) as its principal component, was observed during both dry and rainy months (Fig. 2).

Between August 2007 and August 2008, the confluence point of the tributary rivers (PC) and the dam zone (PD) had low total biomass in the euphotic (1.30 ± 2.0 mm^3. L^{-1} for PC and 1.51 ± 2.0 mm^3. L^{-1} for PD) and aphotic (0.53 ± 0.7 mm^3. L^{-1} for PC and 0.29 ± 0.5 mm^3. L^{-1} for PD) zones. The highest biomass values there occurred only in isolated cases in October 2007 (7.1 mm^3. L^{-1} for PC) and February 2008 (6.7 mm^3. L^{-1} for PD). Both of these were dry months. The phytoplankton biomass was highest near the net cages (PNC) until the beginning of the rainy season (10.81 ± 6.4 $mm^3.L^{-1}$ for Z_{eup}; 7.49 ± 4.9 $mm^3.L^{-1}$ for Z_{aph}). It decreased considerably (Fig. 2) during the rainy months and the overflow events (2008).

Filamentous heterocyte and non-heterocyte cyanobacteria in the functional groups

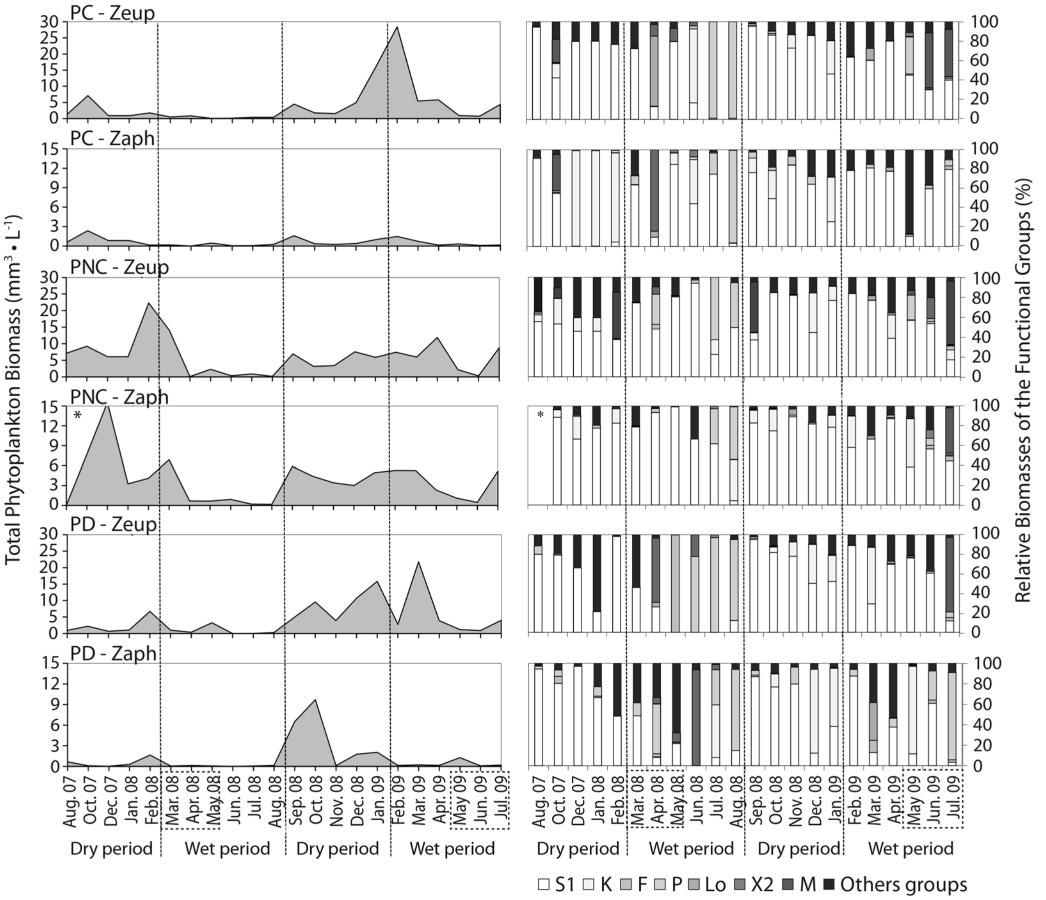

Fig. 2. Variations in the total phytoplankton biomass ($mm^3.L^{-1}$) and relative biomass (%) of the functional groups in the euphotic (Z_{eup}) and aphotic (Z_{aph}) zones at the three collection points in the Argemiro de Figueiredo Reservoir in Paraiba State, Brazil, between August 2007 and July 2009. *No collection.

S1, SN, H1, and MP dominated and accounted for 57.5 % and 97.0 % of the total biomass, respectively, during the dry period (2007 and 2008) (Fig. 2).

Planktothrix agardhii, the principal representative of group S1, contributed the most to the total biomass. It accounted for 95 % at point PC (August 2007), 59 % at PNC (March 2008), and 83 % at PD (February 2008). The 36 % reduction in *P. agardhii* biomass in the aphotic zone at PC (October 2007) favored increases in coccoid cyanobacteria biomass in the functional groups M and K. The latter contributed with more than 90 % of the total biomass. In PNC and PD, reductions in the biomass of this species occurred when the reservoir overflowed.

During the overflow period at the start of the 2008 (rainy season), the cyanobacteria contributed less, and these conditions favored the dominance of other functional groups. Group Lo dominated in the euphotic zone (64.7 % of the total biomass) and X2 dominated in the aphotic zone (84.2 % of the total biomass) at collection point PC. Group X2 (65.6 % of the total biomass) and F (99.0 % of the total biomass) dominated at point PD in the euphotic zone. The contributions of cyanobacterial functional groups remained high at collection point PNC. Reductions in cyanobacteria populations (> 40 %) occurred only when the rainy period ended, which the dominance of group P (maximum 0.02 $mm^3.L^{-1}$) mainly in the euphotic zone (Fig. 2).

At the start of the 2008 dry period, as rainfall decreased, phytoplankton biomass increased (4.48 $mm^3.L^{-1}$ for PC; 6.92 mm^3. L^{-1} for PNC; 4.96 mm^3. L^{-1} for PD). Cyanobacterial dominance was frequently observed (> 90 % of the total biomass) and consisted mainly of Groups S1 and K. During the rainy period, phytoplankton biomass did not change and remained high (13.22 ± 13.2 mm^3. L^{-1} for PC; 8.42 ± 3.1 $mm^3.L^{-1}$ for PNC; 9.48 ± 10.6 mm^3. L^{-1} for PD). The beginning of a new rainfall period in February 2009 caused an overflow event that lasted six months. It reduced phytoplankton biomass (0.73 mm^3. L^{-1} for PC; 0.29 mm^3. L^{-1} for PNC; 0.90 mm^3. L^{-1} for PD) until the end of the period. *Closterium* sp. predominated in Group P and Group M contributed to a biomass increase during this period (4.38 mm^3. L^{-1} for PC; 8.76 mm^3. L^{-1} for PNC; 4.02 mm^3. L^{-1} for PD) (Fig. 2).

Canonical correspondence analysis indicated eigenvalues of 0.299 and 0.128 for the first two axes, respectively (Fig. 3). Pearson's correlation coefficient of environment-species factors for these axes indicated significant relationships between environmental variables and biomass (Table 3). The Monte Carlo test was significant ($p < 0.01$), indicating that ordination did not occur randomly. The canonical coefficients and intra-set correlations demonstrated that the variables related to overflows and reservoir volumes were the most important for axis I ordination (Table 3). These variables contributed to the grouping on the positive side of this axis for overflow months and the negative side during months without overflow. The functional groups F, M, and X2 appeared to be closely correlated to rainy months with overflow. The opposite was true for groups S1, SN, and K, which were associated with the dry months (Fig. 3).

The most important variables on axis 2 were the coefficients of light attenuation, rainfall, and water temperature. On the negative side of the axis were the rainy and dry months with the lowest water temperatures, pH, alkalinity, electrical conductivity, and functional groups P and F. On the positive side were the months with the warmest and most alkaline waters, the greatest coefficients of light extinction, and the functional groups Lo and X2 (Fig. 3).

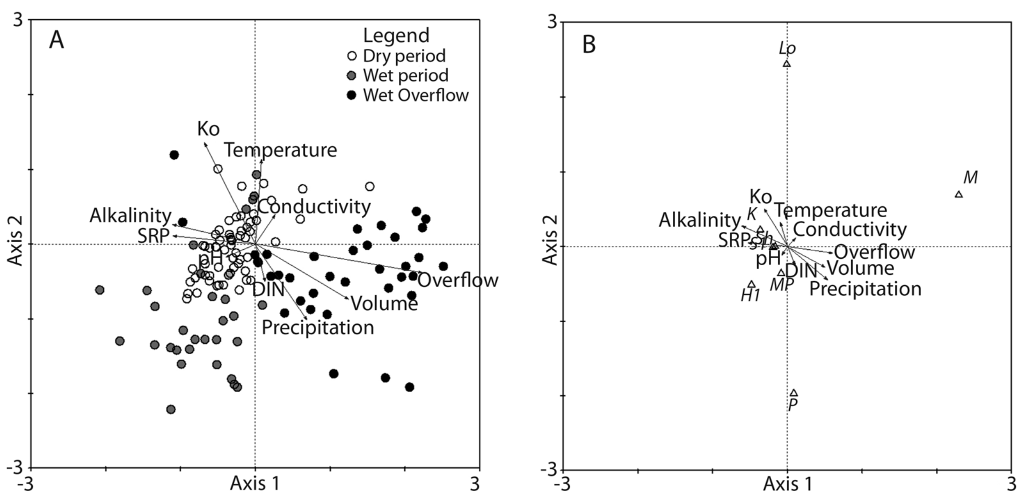

Fig. 3. CCA ordination among the significant abiotic variables measured (a), and the principal phytoplankton functional groups (b) in the Argemiro de Figueiredo Reservoir in Paraíba State, Brazil, between August 2007 and July 2009.

TABLE 3
Statistical synthesis for the first two axes of CCA performed on the phytoplankton functional groups and the abiotic variables in the Argemiro de Figueiredo Reservoir (Brazil)

	Axis 1	Axis 2		Canonical coefficient		Intra-set correlation	
				Axis 1	Axis 2	Axis 1	Axis 2
Eigenvalues	0.299	0.128	Overflow	0.60	-0.07	0.80	-0.12
Accumulated variance in the biotic data (%)	12.6	18.0	Volume	0.30	-0.15	0.41	-0.27
Accumulated variance in the association-environment relationships (%)	47.9	68.3	Precipitation	0.16	-0.25	0.21	-0.46
Association-environment correlation	0.750	0.551	Temperature	-0.09	0.24	-0.11	0.43
Monte Carlo test			K_o	-0.15	0.29	-0.19	0.53
Significance of first canonical axis – p		0.001	pH	-0.07	-0.04	-0.09	-0.08
Significance of all canonical axes – p		0.001	Conductivity	0.02	0.09	0.03	0.16
			Alkalinity	-0.27	0.04	-0.36	0.07
			DIN	0.06	-0.09	0.08	-0.16
			SRP	-0.19	0.02	-0.25	0.04

K_o = coefficient of vertical light attenuation, DIN = dissolved inorganic nitrogen, SRP = soluble reactive phosphorus.

DISCUSSION

The phytoplankton community in the Argemiro de Figueiredo (Acauã) Reservoir consisted of functional groups found in eutrophic, mixed aquatic environments. Algal biomass increased and was influenced by seasonal changes. The largest biomass was recorded during dry periods. Phytoplankton community structure changed and its biomass declined (> 50 %) during the rainy periods mainly when the reservoir overflowed. Intense rainfall causing hydrological instability and overflow can drastically reduce the biomass of cyanobacterial species (Oliveira et al., 2015).

Increasing water flow in the reservoir disturbed the phytoplankton. It altered light availability and reduced pH, electrical conductivity, dissolved oxygen, alkalinity, and biomass. In tropical regions where rainfall is concentrated into just a few months of every year, reservoir volumes can change drastically, disturbing the water column and aquatic communities. These disturbances have a large influence on phytoplankton composition and biomass (Figueredo & Giani, 2005; Câmara et al., 2015).

The long residence time of reservoir water, high evaporation rates, and synergy between high water temperatures and high nutrient concentrations accelerated eutrophication. These factors were also responsible for the dominance of cyanobacteria, especially during the dry season when the functional groups S1, SN, H1, M, K and MP predominated. *Planktothrix agardhii*, the principal representative of functional group S1, was dominant for most of the dry period. It has frequently been found in eutrophic Brazilian reservoirs (Chellapa, Câmara, & Rocha, 2009, b; Bonilla et al., 2012) and throughout the world (Karadžić, Subakov-Simić, Krizmanić, & Natić, 2010). Its biomass is often very high regardless of the season (Poulíčková, Hašler, & Kitner, 2004).

In the present study, the only time in which *P. agardhii* did not dominate was during the rainy season, when reservoir water residence time and temperatures were low and overflow caused significant biomass losses. In these conditions, the species belonging to the functional groups F, P, Lo and X2 prevailed. They are found in meso-eutrophic environments (Reynolds et al., 2002; Padisák et al., 2009). Nevertheless, the proliferation of Groups Lo and X2 phytoflagellates in April 2008 resulted from limiting light conditions (transparency < 0.15 m) as well as nutrient abundance.

When they analyzed phytoplankton functional groups in a Turkish reservoir, Gurbuz, Kivrak, Soyupak and Yerli (2003) reported the presence of Group Lo dinoflagellates during periods when light levels were low.

Functional groups Lo and X2 are sensitive to water mixing, so they dominated only in April 2008 when no movement occurred. By May, the water was clear and mixing, so Group F species prevailed since they are common in these conditions (Reynolds et al., 2002; Padisák et al., 2009). Group P, represented mainly by *Aulacoseira granulata,* predominated when water temperatures fell and light levels increased (Borges, Train, & Rodrigues, 2008; Chellappa et al., 2009a). This group is commonly found in shallow, turbulent, eutrophicated waters (Reynolds et al., 2002; Pádisak et al., 2009). During most of the study period, nitrogen and inorganic phosphorus levels exceeded minimum phytoplankton requirements (3-5 $\mu g.L^{-1}$ soluble reactive phosphorus (SRP) and 80-100 $\mu g.L^{-1}$ dissolved inorganic nitrogen [DIN]) (Reynolds, 1997). The elevated phosphorus and nitrogen concentrations in the reservoir demonstrated that DIN: SRP ratios alone do not explain temporal phytoplankton community dynamics.

The present study showed that seasonality is the principal factor driving the temporal dynamics of phytoplankton communities in eutrophic reservoirs of semiarid regions. This finding concurs with Seip and Reynolds (1995) who reported that the physical factors affected by seasonal gradients explain the distributions and abundances of these organisms. In the Argemiro de Figueiredo Reservoir, the physical and chemical characteristics of the water influenced phytoplankton functional groups structure. Physical factors, particularly overflow events, broke the dominance of cyanobacterial functional groups and opened windows of opportunity for phytoflagellate, coccoid chlorophyceae, diatom, and elongated desmid biomass to increase.

Intensive pisciculture caused significant anthropogenic disturbances in the study reservoir. The greatest phytoplankton biomass occurred at pisciculture sites near the net cages (PNC). Pisciculture interfered with the species compositions of local phytoplankton functional groups and caused cyanobacteria from Groups S1, SN, and K to predominate. Fish ration residues near the net cages enriched nutrient levels in the reservoir system and significantly increased phytoplankton biomass. The shallow water at this point (Z_{max} = 7.7 m) increased interactions with bottom sediments and synergistically enhanced nutrient availability. This area is distant from the reservoir dam and is not, therefore, affected much by overflow events. These conditions favor high cyanobacterial biomass. Pisciculture residues increase nitrogen and phosphorus concentrations in the water column and sediments, which provokes eutrophication (Figueredo & Giani, 2005; Guo, Zhongjie, Xie, & Ni, 2009; Borges, Train, Dias, & Bonecker, 2010). Studies have also shown that Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) can cause ichthyoeutrophication due to their high defecation rates (Lazzaro et al., 2003; Panosso et al., 2007). Borges et al. (2010) reported significant increases in phytoplankton (especially cyanobacterial) biomass after the introduction of pisciculture in the Rosana reservoir (Southeastern Brazil).

In summary, the present study demonstrated that (a) reservoir overflows are natural disturbances that reduce phytoplankton biomass and alter local community structures, (b) pisciculture is an anthropogenic disturbance that increases nutrient availability and stimulates increases in phytoplankton functional groups (mainly cyanobacterial) biomass; and (c) phytoplankton functional groups are reliable sentinels of environment conditions in the reservoirs of tropical semiarid regions.

ACKNOWLEDGMENTS

The authors would like to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico for their financial support through the universal project MCT/CNPq O2/2006 and for the doctoral grant awarded to the first author (Edital MCT/CNPq/CT-Hidro N° 040/2006), as well as the Laboratório de Saneamento da Universidade Federal de Campina Grande and the Laboratório de Microplâncton do Núcleo de Estudos e Pesquisas dos Recursos do Mar (NEPREMAR) at the Universidade Federal da Paraíba.

RESUMEN

Grupos funcionales de fitoplancton en una represa tropical de una región semiárida de Brazil. La estructura de grupos funcionales del fitoplancton y la abundancia de especies varían de acuerdo con las condiciones ambientales. Este estudio investigó los estresores naturales y antropogénicos que afectan la biomasa de grupos funcionales de fitoplancton en una represa (la represa de Argemiro de Figueiredo) en una región semiárida de Brasil. La recolecta de datos fue entre agosto 2007 y julio 2009 de forma bimensual durante el primer año, y de forma mensual durante los últimos dos años. Estos se recolectaron en tres sitios (PC: confluencia del río; PNC: cerca de las jaulas; PD: sitio de la represa). El análisis de las variables abióticas del agua incluyó: temperatura, transparencia, coeficiente de atenuación vertical de la luz, oxígeno disuelto, pH, conductividad eléctrica, alcalinidad, nitrógeno inorgánico disuelto y fósforo reactivo soluble. Las muestras de fitoplancton fueron recolectadas en una botella Van Dorn, y fueron preservadas en lugol acético y cuantificadas utilizando un microscopio invertido para determinar la densidad y la biomasa del fitoplancton, las especies identificadas fueron agrupadas en grupos funcionales. Los datos fueron explorados mediante un análisis de correspondencia canónica. Los análisis individuales fueron hechos para probar la variabilidad espacial y temporal de los datos y los factores que más interfieren con las variables bióticas y abióticas. Los grupos funcionales S1, SN, y K, incluyen las algas filamentosas: *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek, *Cylindrospermopsis raciborskii* (Woloszynska) Seenaya & Subba Raju, y algas cocoides: *Aphanocapsa incerta* (Lemmermann) Cronberg & Komárek, respectivamente dominando los meses cálidos cuando el agua estuvo caliente, turbia y alcalina. El desbordamiento de la reserva funciona como una alteración natural, reduciendo la biomasa del fitoplancton a menos de un 50 % y la dominancia de cianobacterias, promoviendo el dominio de los grupos funcionales F, M, MP, Lo y X2. La llegada de nutrientes debido a la pesca intensiva, asociado con una baja profundidad local (Z_{max} = 7.7 m), cerca de las jaulas (PNC), resulta en una alteración humana significativa que incrementa la prevalencia de los grupos funcionales S1, SN y K, los cuales están compuestos principalmente por cianobacterias. Concluimos que, en las represas, eventos de desborde son perturbaciones naturales que tienen la habilidad para reducir la biomasa del fitoplancton y alterar la estructura de las comunidades locales, y que la pesca intensa es una alteración antropogénica que incrementa la disponibilidad de nutrientes y estimula el incremento de la biomasa de los grupos funcionales que incluyen las cianobacterias. Además, los grupos funcionales de fitoplancton fueron controles confiables de las condiciones ambientales en las represas de las regiones semiáridas tropicales.

Palabras clave: fitoplancton, grupos funcionales, condiciones climáticas, estabilidad de la biomasa, reservorio, región semiárida, factores estresantes naturales y antropogénicos.

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