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The response of zooplankton assemblages to variations in the water quality of four man-made lakes in semi-arid northeastern Brazil

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The response of zooplankton assemblages to variations in the water quality of four man-made lakes, caused by eutrophication and siltation, was investigated by means of canonical correspondence analysis. Monte Carlo simulations using the CCA eigenvalues as test statistics revealed that changes in zooplankton species composition along the environmental gradients of trophic state and abiogenic turbidity were highly significant. Brachionus calyciflorus, Thermocyclops sp. and Argyrodiaptomus sp. were good indicators of eutrophic conditions, whereas B. dolabratus, Keratella tropica and Hexarthra mira were good indicators of high turbidity due to suspended sediments. Overall, our results showed that changes in the water quality of man-made lakes in a tropical semi-arid region have significant effects on the structure of zooplankton assemblages that can potentially affect the functioning of these ecosystems.

INTRODUCTION

Dry lands are located in arid, semi-arid or dry subhumid climatic zones, comprising 41% of all continental areas of the Earth's surface and are home to more than 2 billion people, or approximately one-third of the world population. In Brazil, the dry lands cover an area equivalent to 11% of the national territory, where ∼13% of the Brazilian population lives. It is estimated that around 20% of the dry lands of the planet are already completely desertified and that the desertified areas will increase considerably in the coming decades (Millennium Ecosystem Assessment, 2005).

In tropical semi-arid regions, the droughts and the highly irregular rainfall, together with high evaporation rates, cause the loss of a great part of the surface waters. As a result, almost the entire hydrologic network is intermittent, which constitutes a severe problem for the supply and storage of this essential resource. Therefore, many reservoirs are constructed in these regions with the main purpose of storing water for multiple uses.

In order to guarantee a certain minimum volume of water in these reservoirs, the drainage basins of the reservoirs must occupy an area much larger than the area of the reservoir itself. Thus, an important distinctive characteristic of reservoirs in semi-arid regions is the high ratio between the area of the drainage basin and the area of the reservoir itself (Thornton and Rast, 1993). This important morphometric characteristic of reservoirs in semi-arid regions, together with a negative balance between precipitation and evaporation rates, affects several ecological processes in these ecosystems. They tend to have high concentrations of nutrients,

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suspended solids and salts, favoring eutrophication, siltation and salinization.

The frequent alterations in trophic state, turbidity and salinity in these reservoirs represent an important selective factor for the success of potentially colonizing species. Furthermore, these reservoirs are relatively shallow environments, highly vulnerable to wind action and to oscillations in climatic conditions, which represent other important selective factors for the biota. Hence, the composition and the relative abundance of species in the aquatic communities must be strongly influenced by the variations in the trophic state, turbidity and salinity of the water and can theoretically be used as parameters to indicate the environmental alterations.

Zooplankton has been recommended as regional bioindicators of lake eutrophication (Attayde and Bozelli, 1998; Pinto-Coelho *et al.*, 2005a, b; Burns and Galbraith, 2007; Stemberg and Lazorchack 1994; Straile and Geller 1998), acidification (Pinel-Alloul *et al.*, 1990), watershed disturbances by agriculture (Dodson *et al.*, 2005, 2007) or logging and wildfire (Patoine *et al.*, 2002). Although zooplankton are usually considered to be good indicators of environmental changes and have a fundamental role in energy flow and nutrient cycling in aquatic ecosystems, these organisms have been little studied in aquatic ecosystems in tropical semi-arid regions. Therefore, their potential value as indicators of alterations in the water quality of reservoirs in these regions needs to be assessed. Also, there is an increasing demand by environmental monitoring programs for bioindicators of water quality.

This study attempted to investigate how the trophic state, turbidity and salinity affect the structure of the zooplankton communities in four reservoirs in a tropical semi-arid region. We then assessed the potential of the zooplankton as a bioindicator of the main alterations in the water quality of these reservoirs.

METHOD

Study area

The present study was carried out in the Gargalheiras, Cruzeta, Itans and Boqueirão de Parelhas reservoirs, all of which are located in the Seridó region of the state of Rio Grande do Norte, Brazil (Fig. 1). The four reservoirs are located in the basin of a river of the same name, the Seridó River, which is one of the main

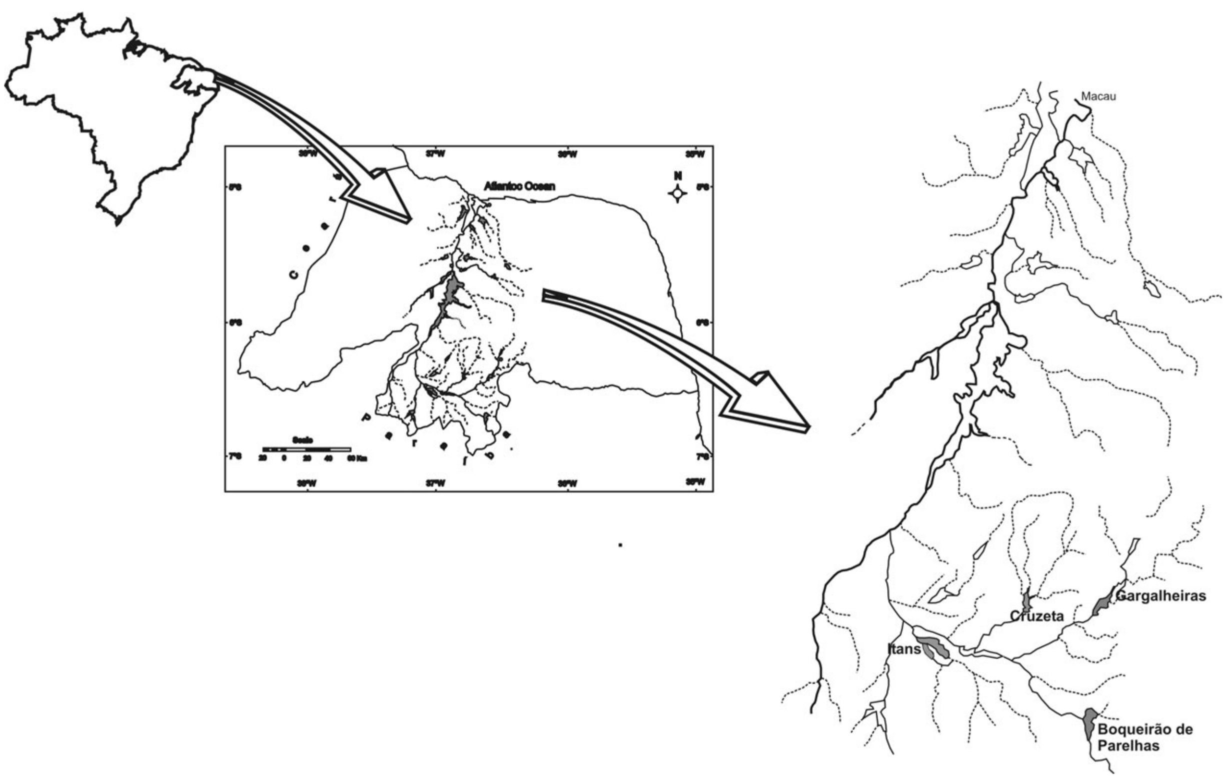

Fig. 1. Location of the study area, highlighting the Gargalheiras, Cruzeta, Itans and Boqueirão de Parelhas reservoirs, state of Rio Grande do Norte, Brazil.

tributaries of the Piranhas-Assu River. This hydrographic basin lies entirely in a semi-arid region, with a mean annual rainfall of 500 mm and a great spatial–temporal irregularity in its rainy season. In general, precipitation levels above 100 mm are only reached between February and May, and the remaining months are marked by an almost complete lack of precipitation. The soil of the areas surrounding these reservoirs is shallow and highly susceptible to erosion during the rainy periods.

Sampling

Water sampling was carried out monthly from March to December 2005, covering both the dry and rainy seasons of the region. Samples were taken at three different points along the longitudinal axis of the reservoir: one in the zone nearest the delta of the main tributary, one in the center of the reservoir and another in the zone nearest the dam.

The water samples were collected with a Van Dorn bottle at 1 m vertical depth intervals and integrated for the collection of 2 L subsamples from each collection point. pH and conductivity were measured *in situ* with a HORIBA model U-23 multiparameter probe. The values of conductivity were used as an approximation for the estimation of salinity. Water transparency was measured with a Secchi disk. Concentrations of chlorophyll *a* (Chl *a*) were determined with a Turner TD 700 fluorometer after filtration of the water through fiberglass filters (Whatman 934-AH) and extraction of the pigments with ethanol at room temperature for ~20 h (Jespersen and Christoffersen, 1988). The concentrations of total phosphorus were determined after digestion of the samples with potassium persulfate by the ascorbic acid method (APHA, 1989). In order to determine the concentrations of total suspended solids (STS), the water samples were filtered with Whatman 934-AH filters previously dried and weighed. The filters containing the particulate matter were again dried at 105°C for ~1 h and then weighed on an analytical balance. This procedure was repeated until a stable weight was established. In order to determine the concentrations of fixed suspended solids (SFS), the filters were incinerated in a muffle furnace at 550°C for 15 min and their ashes were weighed. Volatile suspended solids (SVS) were determined by the difference between the STS and the SFS according to the APHA (APHA, 1989).

The zooplankton samples were collected with a 68 μm mesh plankton net towed vertically. The volume of filtered water was calculated as the product of the net mouth area and the tow depth, assuming a 100% filtering efficiency of the net. The collected material was stored in polyethylene bottles and fixed with Lugol's solution. The organisms were counted after the integration of the samples from the three points of each reservoir, totaling 35 samples of zooplankton, or one integrated sample per month for each reservoir. For abundance estimates, the integrated samples were mixed and 1 mL subsamples were taken with a Stempel pipette. Counting was carried out using an optical microscope in a Sedgwick-Rafter chamber with 1 mL capacity until the coefficients of variation of the most abundant species were lower than 20%.

Statistical analyses

We performed an ANOVA and the Tukey HSD (honestly significant difference) test to test for differences in limnological features between the reservoirs. The data were transformed to natural logarithms to satisfy the premises of homogeneity of variances and normality of the analyses. A principal components analysis (PCA) was used to ordinate the 35 sample units and 9 environmental variables on a few factorial axes with the purpose of reducing the dimensionality of the data and describing the relationships between these variables. The PCA was performed from the linear correlation matrix of the environmental variables after logarithmic transformation of the data, except for the pH data.

A canonical correspondence analysis (CCA) was performed in order to detect the relations between the abundance of the zooplankton species and the environmental variables analyzed. The ordination analyses were performed with the program CANOCO version 4 (Ter Braak, 1986; Ter Braak and Smilauer, 1998). To evaluate the significance of the CCA axes and of the environmental variables which defined these axes, Monte Carlo tests were performed with 999 unrestricted permutations, using the eigenvalues of the axes as test statistics (Ter Braak and Prentice, 1988). Thus, it was possible to test the significance of the environmental variables in determining the ordination patterns of the species and to assess the potential of certain groups of species as indicators of environmental conditions in these reservoirs.

To determine the relationship between the zooplankton community structure and the environmental variables indicating eutrophication, salinization and siltation, we used abundance-weighted averaging to calculate taxon-specific optima along gradients of Chl *a*, conductivity and suspended fixed solids respectively (Ter Braak and Smilauer 1998). Calculations of weighted average optima (WAopt) of zooplankton taxa were carried out using the following equation:

$$\text{WAopt} = \frac{\sum_i^n (A_i \times V_i)}{\sum_i^n A_i}$$

where A_i is the taxon's abundance in sample i, V_i the abundance/concentration of the environmental variable in sample i and n the number of samples.

RESULTS

Environmental variables

High concentrations of total phosphorus were observed in the water of the reservoirs, especially in Gargalheiras and Cruzeta (Table I). Nevertheless, the reservoirs contained very different concentrations of Chl *a*, clearly indicating that there is a high variability in the response of the planktonic algae when faced with high concentrations of phosphorus in these environments. Gargalheiras Reservoir contained a high phytoplankton biomass, while the remaining reservoirs contained low concentrations of Chl *a*, despite their high concentrations of total P (Table I). Therefore, Gargalheiras Reservoir is the only one that can be safely classified as eutrophic, as in addition to its high concentrations of total P, it has equally high concentrations of Chl *a* and suspended particulate organic matter. The major part of the STS in Gargalheiras Reservoir was composed of organic matter, as indicated by the results of SVS. On the other hand, in Cruzeta Reservoir, the STS were mostly of inorganic origin, as indicated in the results for the SFS. The remaining reservoirs showed a more even distribution of the two fractions of suspended solids. The high concentrations of SFS in Cruzeta Reservoir are probably related to its shallow depth, which facilitates re-suspension of the sediments, thus reducing water transparency. The mean pH values did not differ among the reservoirs. The mean values of conductivity were significantly higher in Boqueirão de Parelhas and Gargalheiras (Table I).

In the PCA, the two first factors together explained 72.4% of the total variance of the environmental variables data. The first factorial axis ($\lambda_1 = 0.493$) explained 49.3% of the variance of the data, whereas the second axis ($\lambda_2 = 0.231$) explained 23.1% of this variance. The ordination diagram shows the coordinates of the sample units and of the environmental variables on the two first factorial axes (Fig. 2). In the PCA, the coordinates of the environmental variables represent the angular coefficients of the linear functions that describe the relationships between these variables and the factorial axes of the ordination. Thus, the position of the coordinate of a given environmental variable in relation to the origin (0,0) of the diagram indicates the variation rate of this variable along each axis. The vector which links the point of origin (0,0) of the diagram to the point referring to the coordinate of the variable in question points to the sample units where the value of this variable increases more rapidly.

For the interpretation of the factorial axes, the correlations of the environmental variables with the respective axes were calculated (Table II). The concentrations of total and volatile solids, total P and Chl *a* showed the highest positive correlation with the first axis, whereas the Secchi disk depth and the mean depth showed strong negative correlations with this axis. The second axis showed a strong positive correlation with the

Table I: Means and standard deviations of the limnological variables in the four reservoirs

Variables	Parelhas		Itans		Cruzeta		Gargalheiras		ANOVA	Tukey test
Area (ha)	1326.68		1340		748.79		780			
Maximum depth (m)	29		23		14.5		25			
Drainage (watershed) area (km^2)	1519		1268		1400		2400			
	Mean	DP	Mean	DP	Mean	DP	Mean	DP	*P*-value	$\alpha = 0.05$
Zm (m)	5.8	0.2	5.1	0.1	2.7	0.2	4.7	0.1	0.000	P>I>G>C
CHL (μg L^{-1})	3.4	2.8	3.4	4.4	7.1	6.1	43.4	19.7	0.000	G>P=I=C
TP (μg L^{-1})	29.6	19.8	51.0	16.3	96.3	26.0	89.7	13.8	0.000	G=C>I>P
STS (mg L^{-1})	9.8	2.6	6.5	2.2	26.4	8.3	19.2	8.9	0.000	G=C>P>I
SVS (mg L^{-1})	4.1	1.4	2.9	2.2	7.4	2.4	15.2	7.2	0.000	G>C=P=I
SFS (mg L^{-1})	5.7	2.5	3.7	1.1	19.0	7.7	4.0	2.5	0.000	C>P=I=G
SEC (m)	1.1	0.2	1.6	0.2	0.5	0.1	0.5	0.1	0.000	I>P>C=G
pH	8.4	0.4	8.5	0.3	8.5	0.6	8.8	0.6	0.084	P=I=C=G
CE (mS cm^{-1})	0.8	0.1	0.5	0.0	0.6	0.1	0.8	0.1	0.000	P=G>C>I

Results of the ANOVA and the Tukey test for differences in the variables between the reservoirs. Zm, mean depth; CHL, chlorophyll *a*; TP, total phosphorus; STS, suspended total solids; SVS, suspended volatile solids; SFS, fixed suspended solids; Sec, Secchi disk depth; CE, conductivity.

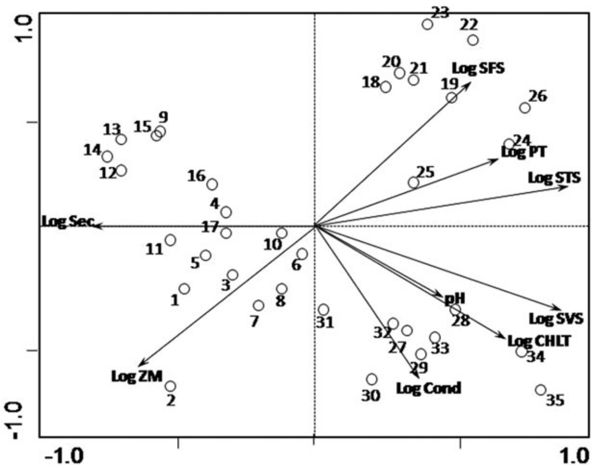

Fig. 2. Ordination diagram by PCA of the 35 sample units based on the correlation matrix of the nine environmental variables. Sample units of Boqueirão de Parelhas (1–8), Itans (9–17), Cruzeta (18–26) and Gargalheiras (27–35) reservoirs (see Table I for abbreviations).

Table II: Correlation coefficients between environmental variables and the first two PCA axes

	Axis 1	Axis 2
TP	0.75	0.25
Zm	−0.67	−0.66
CHL	0.67	−0.58
STS	0.95	0.16
SVS	0.84	−0.40
SFS	0.49	0.71
SEC	−0.91	0.05
pH	0.35	−0.20
CE	0.39	−0.70

See Table I for abbreviations.

concentrations of SFS and a strong negative correlation with conductivity and mean depth. It can be observed in the ordination diagram (Fig. 2) that the sample units from Gargalheiras (27–35) and Cruzeta (18–26) were positively correlated with the first PCA axis, whereas the sample units from Itans (9–17) and Boqueirão de Parelhas (1–8) were negatively correlated with this axis. In relation to the second axis of the PCA, the sample units from Gargalheiras and Parelhas were negatively correlated, whereas those from Cruzeta and Itans were positively related to this axis.

These results indicate that the sample units from Gargalheiras Reservoir were strongly associated with the highest concentrations of Chl *a* and SVS and with the highest values of conductivity, whereas the sample units from Cruzeta Reservoir were strongly associated with the highest concentrations of SFS and with the lower mean depths. The highest concentrations of total P and STS were strongly associated with these two reservoirs, and, due to this fact, the vectors of these two variables were positioned between the coordinates of the sample units of these reservoirs. The sample units of Boqueirão de Parelhas Reservoir were strongly associated with the highest values of mean depth and the lowest concentrations of total P and of total and SFS. The sample units of Itans Reservoir were strongly associated with the lowest concentrations of total and SVS and with the lowest concentrations of Chl *a*. Overall, the pattern of variation found in the limnological variables among the four reservoirs is well reproduced by these first two PCA ordination axes.

Zooplankton community

During the study period, 21 zooplankton species were recorded. The occurrence frequencies and mean densities of the taxa found in the four reservoirs are shown in Table III. The species that occurred generally with the highest frequencies were: *Brachionus falcatus*, *Brachionus* sp., *Filinia terminalis*, *Hexarthra mira*, *Keratella americana*, *K. tropica*, *B. dolabratus*, *B. havanensis*, *Ceriodaphnia cornuta*, *Diaphanosoma spinulosum*, *Moina minuta*, *Notodiaptomus cearensis*, *Mesocyclops* sp., *Thermocyclops* sp. and calanoid and cyclopoid copepodids and nauplii. However, the species occurring with the highest frequencies were not always the same as those with the highest densities. Among the species with the highest densities were: *Brachionus* sp., *K. tropica*, *B. dolabratus*, *F. terminalis*, *H. mira*, *C. cornuta*, *N. cearensis* (adults, copepodids and nauplii). Overall, Itans and Cruzeta reservoirs supported the highest densities of rotifers, whereas Parelhas and Gargalheiras supported the highest densities of copepods.

A CCA was used to investigate the response of each species to the environmental variables analyzed. Among the nine environmental variables, only conductivity, mean depth, Secchi disk depth, Chl *a* and SFS were selected for inclusion in the CCA regression model. The remaining variables did not explain any meaningful proportion of the residual variance, and were therefore excluded from the analysis (Table IV). The results of the CCA indicate that the first two axes of the ordination defined by the five environmental variables selected explained collectively 42.5% of the variance in the weighted mean of the species (Table V). The Monte Carlo test with 999 permutations demonstrated that both the first canonical axis ($\lambda_1 = 0.607$; F-ratio=12.219) and the sum of all canonical axes (trace=1.053; F-ratio=6.131) were highly meaningful ($P = 0.001$).

Table III: List of zooplankton taxa found in the four reservoirs

Species	Boqueirão de Parelhas	Reservoirs Itans	Cruzeta	Gargalheiras
Protozoa				
Testate amoebae	100.0 (92.4)	100.0 (28.9)	66.7 (1.5)	88.9 (284.8)
Rotifera				
B. calyciflorus		22.2 (0.3)	44.4 (3.3)	44.4 (10.8)
B. dolabratus	12.5 (0.2)	77.8 (3.49)	100.0 (46.7)	44.4 (0.4)
B. falcatus	100.0 (8.1)	88.9 (2.3)	100.0 (6.8)	44.4 (0.6)
B. havanensis	12.5 (0.1)	44.4 (0.4)	100.0 (5.7)	88.9 (8.5)
Brachionus sp.	37.5 (0.5)	100.0 (256.8)	100.0 (130.7)	33.3 (0.2)
F. terminalis	37.5 (2.6)	100.0 (15.0)	100.0 (44.6)	100.0 (14.5)
F. opoliensis		44.4 (0.8)	77.8 (2.9)	
Hexarthra sp.	75.0 (4.6)	100.0 (14.4)	100.0 (109.1)	55.5 (1.3)
K. americana		100.0 (25.0)	100.0 (16.4)	22.2 (0.2)
K. tropica	12.5 (0.2)	100.0 (88.0)	100.0 (230.2)	66.7 (11.9)
Lecane sp.1	12.5 (0.1)	22.2 (0.2)	11.1 (0.4)	22.2 (0.3)
Lecane sp. 2	100.0 (51.3)			
Cladocera				
C. cornuta	100.0 (25.8)	100.0 (9.0)	77.8 (3.9)	22.2 (3.1)
D. spinulosum	100.0 (12.2)	88.9 (2.1)	100.0 (8.0)	77.8 (2.5)
M. minuta	75.0 (6.1)	100.0 (6.1)	100.0 (9.9)	22.2 (0.3)
Neonats	87.5 (3.1)	77.8 (1.6)	66.7 (1.2)	11.1 (0.2)
Copepoda				
Argyrodiaptomus sp.				44.4 (0.6)
Calanoida Copepodites	87.5 (8.1)	100.0 (24.2)		100.0 (8.6)
Cyclopoida Copepodites		33.3 (0.7)		22.2 (1.0)
Mesocyclops sp.	87.5 (2.2)	100.0 (3.4)	88.9 (7.6)	77.8 (7.8)
Calanoida Nauplii	100.0 (27.9)	100.0 (51.4)	100.0 (128.0)	100.0 (33.7)
Ciclopoida Nauplii		100.0 (0.7)	100.0 (4.7)	8.9 (1.0)
Notodiaptomus sp.	100.0 (63.1)	100.0 (32.0)	100.0 (27.1)	100.0 (85.4)
Thermocyclops sp.		33.3 (0.7)		100.0(13.7)
Other taxa				
Chaoborus sp.		33.3 (0.2)	66.7 (1.1)	22.2(0.1)

Values are relative frequency of occurrence (%) and in parenthesis mean density (ind. L^{-1}) of each taxon over all samples.

Figure 3 shows the CCA ordination diagram with only the two first and most important ordination axes. This diagram shows the patterns of variation in the specific composition of the community, which can be explained by the five environmental variables, and also shows the distribution patterns of the species along each environmental variable or gradient. The vectors of the environmental variables shown in this diagram explained collectively 82.7% of the variance in the weighted means of the species in relation to the five environmental variables (Table V).

Based on Fig. 3, it can be inferred that *Argyrodiaptomus* sp., *Thermocyclops* sp. and *B. calyciflorus* were principally found in more eutrophic habitats, in this case Gargalheiras Reservoir. On the other hand, the projection of the species in the vector which represents a gradient of the concentrations of SFS shows that

Table IV: Results of the Monte Carlo test with 999 permutations for the selection of the environmental variables which could explain a significant proportion of the variance of the species

Variables	Variance explained	*F*-ratio	*P*-value
CE	0.42	8.56	0.0010
Zm	0.30	7.26	0.0010
SEC	0.14	3.68	0.0010
CHL	0.10	2.80	0.0030
TP	0.04	1.08	0.3180
pH	0.05	1.47	0.1360
STS	0.03	0.86	0.5370
SVS	0.02	0.54	0.8440
SFS	0.09	2.56	0.0160

See Table I for abbreviations.

Table V: Eigenvalues of the first four CCA axes and their respective cumulative proportions of the variance of the species

	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.60	0.26	0.09	0.06
% Variance	29.6	42.5	47.0	50.2
Correlations	0.96	0.83	0.82	0.87
% Variance	57.7	82.7	91.5	97.6

Species-environment correlations and cumulative proportions of the variance of the relationships between the species and the environmental variables.

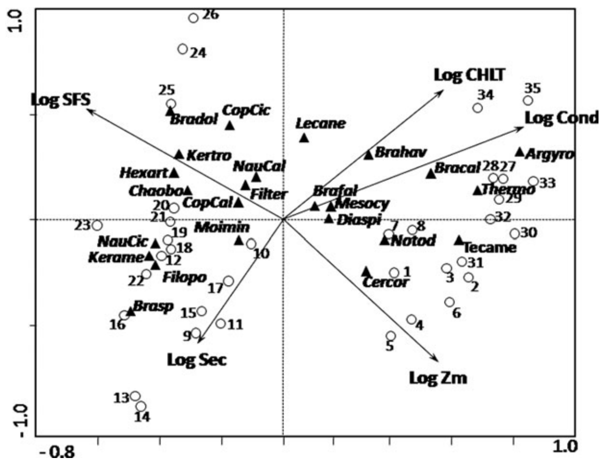

Fig. 3. Ordination diagram by CCA of the zooplankton species and of the sample units of Boqueirão de Parelhas (1–8), Itans (9–17), Cruzeta (18–26) and Gargalheiras (27–35) reservoirs. Circles represent the sample units, triangles the species and vectors the environmental variables. The vectors of the environmental variables are: CHL, chlorophyll *a*; Sec, Secchi disk depth; Cond, conductivity; ZM, mean depths. The taxa shown are: Diaspi, *Diaphanosoma spinulosum*; Tecame, Thecamebae; Kertro, *Keratella tropica*; Hexart, *Hexarthra* sp.; Moimin, *Moina minuta*; Cercor, *Ceriodaphnia cornuta*; Neonat, neonata; CopCal, copepodids of Calanoida; CopCic, copepodids of Cyclopoida; NauCal, Naupii of Calanoid; NauCic, Nauplii of Cyclopoida; Notod, *Notodiaptomus cearensis*; Mesocy, *Mesocyclops* sp.; Brasp, *Brachionus* sp.; Lecane, *Lecane* sp.; Bradol, *Brachionus dolabratus*; Brafal, *Brachionus falcatus*; Filopo, *Filinia opoliensis*; Kerame, *Keratella americana*; Chaobo, *Chaoborus* sp.; Brahav, *Brachionus havanensis*; Thermo, *Thermocyclops* sp.; Bracal, *Brachionus calyciflorus*; Argyro, *Argyrodiaptomus* sp. Filter, *Filinia terminalis*.

B. dolabratus, *K. tropica* and *H. mira* were predominantly found in more turbid habitats, specifically in Cruzeta Reservoir. Thus, the approximate species composition in each sample unit can be inferred by the proximity of the coordinates of the species to the coordinates of the sample units. In order to identify the distribution patterns of the species along the environmental gradients, the coordinates of the species are projected perpendicularly along the vectors of the environmental variables. The projection order of the points in the vectors corresponds approximately to the ranks of the weighted means of the species in relation to the variable in question. Hence, the projection of the points of the species in the vectors of each environmental variable allows for an approximate visualization of the distribution centers of the species along the environmental gradient in question (ter Braak, 1986).

The abundance and distribution of each zooplankton taxon along the environmental gradients of eutrophication, salinization and siltation in the reservoirs can also be investigated by calculating their abundance-weighted optima of Chl *a*, conductivity and suspended fixed solids, respectively. For example, the copepods *Argyrodiaptomus sp.* and *Thermocyclops* sp. and the rotifers *B. calyciflorus* and *B. havanensis* showed their abundance-weighted optima at the highest levels of algal biomass, whereas other species of rotifers (*Brachionus sp*, *F. opoliensis*, *K. americana* and *H. mira*) and the cladocerans *C. cornuta* and *M. minuta* were generally more abundant at much lower concentrations of Chl *a* (Table VI). A similar pattern was found for conductivity, which is highly correlated with the trophic state of the reservoirs. On the other hand, these results confirm that the rotifer *B. dolabratus* showed its abundance-weighted optima at the highest concentration of suspended fixed solids, whereas the copepods *Thermocyclops*, *Argyrodiaptomus* and *Notodiaptomus* were more abundant in less turbid waters (Table VI).

DISCUSSION

It has long been recognized that an increase in phosphorus concentration can cause an increase in phytoplankton productivity, resulting in the eutrophication of lakes and reservoirs. However, a discrepancy was observed between the concentrations of total phosphorus and the phytoplankton biomass in the reservoirs

Table VI: Abundance-weighted optima of Chl a and fixed suspended solids concentrations and of electric conductivity for the zooplankton taxa found in the four reservoirs

	Chl *a* (μg L^{-1})	Conductivity (mS cm^{-1})	SFS (mg L^{-1})
Argyrodiaptomus sp.	53.18	0.87	4.78
B. calyciflorus	32.35	0.81	7.87
Brachionus sp.	2.36	0.49	9.27
B. dolabratus	10.93	0.63	24.07
B. falcatus	8.20	0.69	13.45
B. havanensis	37.08	0.78	10.49
C. cornuta	6.57	0.73	7.35
Chaoborus spp.	9.69	0.54	18.57
Copepodits of Cyclopoids	13.61	0.65	17.50
Copopodits of Calanoids	10.25	0.60	11.18
D. spinulosum	9.40	0.71	10.08
F. opoliensis	4.29	0.50	16.94
F. terminalis	9.77	0.64	7.95
H. mira	6.82	0.60	12.84
K. americana	5.07	0.52	10.89
K. tropica	9.89	0.60	16.06
Lecane sp.	22.05	0.65	14.77
Mesocyclops sp.	21.77	0.67	10.39
M. minuta	6.77	0.56	8.68
Nauplii of Cyclopoids	8.52	0.57	13.55
Nauplii of Calanoids	10.96	0.65	11.65
Neonats	7.05	0.65	8.0
N. cearensis	17.95	0.73	5.78
Protozoa (Thecamoeba)	23.43	0.77	3.41
Thermocyclops sp.	41.48	0.80	4.60

studied. The availability of light and/or nitrogen might possibly also be important factors limiting primary production in some of these environments (Canfield and Bachmann, 1981; Smith, 1982). According to more adequate trophic classification criteria for semi-arid regions, concentrations above 60 $\mu g\,L^{-1}$ total phosphorus and 12 $\mu g\,L^{-1}$ Chl *a* are indicative of an eutrophic state (Thornton and Rast, 1993). Therefore, we can classify Gargalheiras, Cruzeta and Itans reservoirs as eutrophic and Boqueirão de Parelhas Reservoir as mesotrophic, based on the average concentrations of total phosphorus. If the trophic classification is based on the average values of Chl *a*, then we can still classify Gargalheiras Reservoir as eutrophic, the other reservoirs can be considered to be mesotrophic.

The ordination of the zooplankton community by CCA showed that the community variation patterns were significantly related to the environmental heterogeneity patterns observed in the reservoirs. The five environmental variables, Chl *a*, conductivity, mean depth, Secchi disk depth and SFS, significantly explained the principal variations in the species composition of the zooplankton community. Our hypothesis that the trophic state, turbidity and salinity would be determining factors for the community organization was confirmed by the results of the ordination.

The ordination of the community with the CCA technique allowed for an examination of the zooplankton community distribution patterns of the different species in the sample units, a direct evaluation of the species' response to the environmental variation patterns, and therefore the evaluation and testing of the indicative properties of certain groups of zooplankton species to some important environmental factors in the reservoirs. Thus, the species distribution patterns along the main environmental gradients showed that *Argyrodiaptomus* sp., *Thermocyclops* sp. and *B. calyciflorus* had abundance peaks in environments with higher concentrations of Chl *a*, that is, more eutrophic environments; whereas *B. dolabratus*, *K. tropica* and *H. mira* were more abundant in more turbid environments, with higher concentrations of SFS, and *C. cornuta* and *N. cearensis* had higher densities in environments with greater mean depths.

The responses of the zooplankton community along a spatial gradient of trophic level, salinity and turbidity can be used for practical purposes in environmental monitoring. The attempt to use organisms as indicators of environmental conditions provides early signs of environmental stress in the ecosystems from observations of the responses of these organisms to certain natural or anthropogenic disturbances (Schindler, 1987). However, there is no intention to substitute the conventional methods for the measurement of the environmental variables, which can be measured directly by monitoring the physical and chemical variables of the environment, but to make use of the studies of the zooplankton community as an auxiliary method in the monitoring of these areas.

Among the species identified as indicators of eutrophication in these reservoirs as well as in other regions, the rotifer *B. calyciflorus* stands out for its great tolerance to extremely eutrophic environments (Sládecek, 1983) and to high conductivity (Berzins and Pjeler, 1989). Studies by Bernardi and Giussani (Bernardi and Giussani, 1990) and Gilbert (Gilbert, 1994) demonstrated that the feeding and reproductive rates of these rotifers in the presence of cyanobacteria in eutrophic environments are not affected, which means that their tolerance to these factors explains their high densities in Gargalheiras Reservoir.

On the other hand, in relation to the calanoid copepods, research carried out principally in temperate regions by Quintana *et al*. (Quintana *et al*., 1998) and in some tropical reservoirs (Bonecker *et al*., 2007) indicated that populations of calanoids tend to be reduced in eutrophic environments. Studies in tropical regions by Rocha *et al*. (Rocha *et al*., 1997) and Pinto-Coelho *et al*. (Pinto-Coelho *et al*. 2005a, b) agree with the general patterns described in the literature. However, the results obtained by Tundisi and Matsumura-Tundisi (Tundisi and Matsumura-Tundisi, 1990), Matsumura-Tundisi and Tundisi (Matsumura-Tundisi and Tundisi, 2005) and in the present study point to other structural patterns of the zooplankton communities. Calanoids are found both in mesotrophic and in eutrophic environments, as is the case of *N. cearensis*, found in high densities both in the mesotrophic Boqueirão de Parelhas Reservoir and in the eutrophic Gargalheiras Reservoir, and *Argyrodiaptomus* sp., found only in Gargalheiras Reservoir, indicating that perhaps these patterns are not valid for all regions, neither for tropical nor much less for semi-arid regions. Thus, studies by Reid (Reid, 1989) and Panosso *et al*. (Panosso *et al*., 2003) indicated that the species of the genus *Notodiaptomus*, as well as the cyclopoid genus *Thermocyclops*, is able to reach high densities in eutrophic environments, dominated by cyanobacteria, by making use of small colonies as a feeding resource besides other groups of phytoplankton and protozoa.

On the other hand, the high abiogenic turbidity present in these reservoirs allows rotifers to become more abundant in relation to cladocerans (Pedrozo and Rocha, 2005). Among the cladocerans, the species of the genus *Moina* and *Diaphanosoma* is generally favored

(Cuker and Hudson, 1992; Maia-Barbosa and Bozelli, 2006). Thus, the rotifer species *B. dolabratus*, *K. tropica* and *Hexarthra* sp., identified as indicators of turbid environments, are found in higher densities mainly in Cruzeta Reservoir, where the shallow depth and the wind action promote a high re-suspension of sediments into the water column. The tolerance of this group to these environments is due to their ability to avoid the ingestion of inorganic particles, through sensor cells present in the mouth region (Pedrozo and Rocha, 2005), promoting a greater adaptive success of this group in relation to the others. Moreover, according to Thorp and Mantovani (Thorp and Mantovani, 2005) rotifers probably do better in turbid waters because the negative effects of competition and predation are partially alleviated by high suspended sediment loads, which affects substantially their predators (e.g. cyclopoid copepods) and food competitors (cladocera).

Finally, we observed a major differentiation in the structure of the zooplankton community in these reservoirs. On the one hand, Itans and Cruzeta reservoirs support dense populations of rotifers, and on the other, Gargalheiras and Boqueirão de Parelhas support high densities of copepods. The later reservoirs, despite exhibiting different trophic states, had a greater conductivity which might have selected against rotifers in favor of copepods.

To conclude, our results confirm our hypothesis that zooplankton communities significantly respond to major changes in the water quality of reservoirs in semi-arid regions driven mainly by eutrophication, siltation and salinization due to evaporation. Therefore, they should be used in biomonitoring programs of water quality in these dry lands, where the sparse water resources often limit both human and wildlife development.

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