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Seasonal and diel stability of limnological parameters and habitat structure in a floodplain lake silted by bauxite tailings (Lago Batata, Pará, Brazil)

by

D.S.C. Lin & É. Pellegrini-Caramaschi

M.Sc. Daniel Sheanan Colmenero Lin & Érica Pellegrini-Caramaschi, Laboratório de Ecologia de Peixes, Departamento de Ecologia, Instituto de Biologia, Universidade Federal do Rio de Janeiro, 21940-540 Rio de Janeiro/RJ, Brazil; e-mail: sheanan@hotmail.com; erica@biologia.ufrj.br

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Abstract

We examined the effects of the structural consequences of siltation in an Amazonian clearwater lake on the diel and seasonal stability of water transparency, temperature, dissolved oxygen concentration, and dissolved oxygen saturation. For 10 years, Batata Lake received tailings (water and clay), generated from bauxite processing. The level of the lake bottom rose, which created periodically flooded areas colonized by stands of wild rice (*Oryza glumaepatula*) and primary-successional *igapó* vegetation. Structural factors (water level, presence or absence of tailings, wild rice, and *igapó* forest) and limnological parameters were related through multivariate analyses. Variables were measured on seasonal and diel cycles at the surface and bottom of the natural and silted areas, in the *igapó* and limnetic zones. ANOVA was applied to compare coefficients of variation (seasonal and diel cycles) of the variables and differences among areas or zones. Temperature increase, lower levels of dissolved oxygen, greater instability of those factors and the establishment of wild rice stands were related to transparency decrease (clay particles suspension) and clay deposition (shallower depth). The primary-successional *igapó* forest did not maintain stable habitat conditions, as did the natural *igapó*.

Keywords: **Amazon, floodplain lake, *igapó* forest, stability, diel cycle, seasonality**.

Resumo

São estudados efeitos de alterações estruturais do hábitat decorrentes do assoreamento de um lago amazônico de águas claras sobre a estabilidade temporal da transparência, temperatura, concentração e saturação de oxigênio dissolvido. O lago Batata recebeu por 10 anos o rejeito, contendo água e argila, oriundo do beneficiamento da bauxita, o que elevou o leito, criando hábitats periodicamente inundados. Estes foram colonizados por bancos de arroz-bravo (*Oryza glumaepatula*) e vegetação de igapó em estágio de sucessão primária. Quota fluviométrica, presença/ausência de rejeito, arroz-bravo e igapó foram relacionados às variáveis limnológicas (ritmos sazonal e nictemeral) medidas na superfície e fundo das áreas natural e assoreada, nas regiões de igapó e limnética. A ANOVA foi utilizada para comparar coeficientes de variação diários e sazonais das variáveis e diferenças entre áreas/regiões. Aumento de temperatura, menores níveis de oxigênio dissolvido, maior instabilidade daqueles fatores e desenvolvimento de bancos de arroz bravo gerados pelo assoreamento, estão principalmente relacionados à queda da transparência devido a partículas de argila em suspensão e à elevação do leito. O igapó em estágio de

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sucessão primária na área assoreada ainda não produziu cobertura capaz de manter condições de hábitat estáveis como as verifícadas em regiões de igapó natural.

Introduction

The immense richness of the fauna and flora of the Amazon basin can be attributed to niche diversity (ROBERTS 1972). Fluctuations of the water level, habitat morphology, topography, vegetation, physical, chemical and physico-chemical factors, habitat stability and productivity available to the food web are some components of conditions associated with niche diversity. The flood pulse is the main force controlling biota in river-floodplain systems, resulting in morphological, anatomical, physiological, phenological, or ethological adaptations, and resulting in characteristic communities (JUNK 1989). Nevertheless, human activities upon Amazonian ecosystems (e.g., LEITE & BITTENCOURT 1991; PEREIRA FILHO 1991; BOZELLI 1992, 1994; FERREIRA 1993; PANOSSO et al. 1995; BOZELLI et al. 2000) threat the close relationships between aquatic fauna and flora, and the environment, and researches are necessary to understanding factors that afect and mantain the dynamic equilibrium of this ecosystems (ESTEVES 2000).

This study is part of a major research, where LIN (2003) approached the effects of the siltation of about 30 % of the area of an Amazonian floodplain lake (ESTEVES et al. 1990) on the habitat conditions and dynamics and the reflexes upon distribution, structure and fish community's resilience. We examined the effects of siltation on basic limnological variables such as transparency, temperature, and concentration and saturation of oxygen. The lake bottom rose and created periodically flooded areas (ESTEVES 2000) which were colonized by stands of wild rice (*Oryza glumaepatula*) (ENRICH-PRAST 2000) and *igapó* vegetation in the primary successional stage (BARBIERI 1995; BARBIERI et al. 2000). Structural factors (water level, presence or absence of tailings, wild rice, and *igapó* forest) and limnological parameters were related through multivariate analyses, and were measured in the *igapó* and limnetic zones of the natural and silted areas, to characterize four different habitats. Measurements were recorded in both seasonal and diel cycles, at the surface and bottom in the natural and silted areas, to determine the consequences of structural changes for the stability of habitat conditions. There is a vast literature on the limnology of Batata Lake (e.g., PANOSSO 1993; ROLAND & ESTEVES 1993; FERRÃO-FILHO & ESTEVES 1994; ESTEVES et al. 1994; CALLISTO & ESTEVES 1996a, b; ESTEVES & ENRICH-PRAST 1997; ROLAND & ESTEVES 1998; BOZELLI et al. 2000). Most of the reports assessed the ecological impact of bauxite tailings upon limnological parameters and the aquatic biota. However, few have treated the intrinsic characteristics of the *igapó* zone, concentrating rather on the limnetic zone of the lake. Our study compared the limnetic and *igapó* zones. Presumably, the *igapó* structure has stabilizer effect on the aquatic system, and, therefore, the silted area would present less stable habitat conditions.

The stability, productivity and conditions of an ecosystem may act upon several levels of biological complexity and certain conditions can limit the sucessional development in an ecosystem (ODUM 1971; MARGALEF 1977, 1986; PIANKA 1988). The flood time, as a constraint factor to the vegetable structure complexity, lead to the formation of different compartments in relation to the structure of the dominant producers. In permanently aquatic zones, phytoplankton and periphytic algae prevail. In zones of long flood time prevail macrophytes, and in zones of smaller flood time prevails the *igapó* forest. We registered the dominant vegetable structure in each compartment, commenting about effects on the remaining variables. Possible reflexes of the habitat conditions and dynamics on the aquatic biota, particularly the ichthyofauna were investigated by LIN (2003).

Study area

The district of Porto Trombetas is located in the municipality of Oriximiná in western Pará State, 100 Km west of the confluence of the Trombetas and Amazonas rivers (LAPA 2000). Batata Lake is located on the right bank of the lower course of the Trombetas River, which is permanently connected to the lake (1°25' and 1°35'S, 56°15' and 56°25'W) (Fig. 1). The lake has clear waters and is surrounded by *igapó* forest (sensu PRANCE 1980). The system undergoes fluctuations in water level of about 8 meters annually (Fig. 2), giving Batata Lake a lotic character during the river's flood stage, and lentic during other periods (ESTEVES 2000).

Bauxite is mined in the highlands of the lower Trombetas River, and for ten years (1979-1989), tailings from bauxite processing were discarded into Batata Lake, silting over an area of about 630 ha (LAPA 2000). Bauxite tailings are composed of clay, chemically inert particles of oxides of aluminum and iron, silicates, and water (CALLISTO & ESTEVES 1996a). The predominant fraction is particles less than 0.49 μm in diameter (CALLISTO & ESTEVES 1996b). Deposition of these tailings raised the bottom of the lake about 5 to 6 meters (BARBIERI 1995). Extensive areas of *igapó* were covered, with consequent death of part of the vegetation, and new, periodically flooded areas were created (ESTEVES 2000). The area has been colonized naturally and through planting of seedlings of *igapó* forest species (BOZELLI et al. 2000), and wild rice has established itself over about 50 ha (BOZELLI & ESTEVES 2000).

Material and methods

Sampling

Sampling for measurement of limnological parameters was carried out in March, June, September and December 2001 and March 2002, corresponding respectively to the river stages of filling 1, flood, drawdown, dry, and filling 2. Four sample areas were defined: natural area/*igapó* zone, natural area/-limnetic zone, silted area/*igapó* zone, and silted area/limnetic zone. The *igapó* remained emerged during the dry season, and measurements were made in the limnetic zone, which was subdivided into shallow waters (limnetic 1) and deep waters (limnetic 2). Parameters analyzed were: transparency (Secchi disk), water level (given by MRN/SA), surface and bottom measurements of: temperature (FAC-400 thermometer), dissolved oxygen concentration and dissolved oxygen saturation (oxymeter YSI-85), presence or absence of: bauxite tailings, *igapó* forest, and stands of wild rice. The diel cycles of transparency, temperature, dissolved oxygen concentration, and dissolved oxygen saturation were characterized by measurements taken at 16:00 h, 20:00 h, 04:00 h, 08:00 h, and 13:00 h, following fish sampling by gillnets associated to this research.

During the filling phase, in the natural and silted areas, the sizes of submerged parts of individuals of *O. glumaepatula* were measured. The daily growth of the wild rice was estimated by recording the water level from 2001 to 2002 during the dry-season phase, when seeds germinate, until the filling phase. We estimated the time that these areas remained flooded, and the unevenness between natural and silted wild rice areas, by using water level data associated with depth data.

Data analysis

Analysis of variance (ANOVA) (KREBS 1989) and Tukey-Krammer test (ZAR 1984) were applied to data (tested by Kolmogorov-Smirnov's normality test) for transparency, temperature, dissolved oxygen concentration, and dissolved oxygen saturation to verify whether these differed among areas or zones.

In order to test which area or zone would show greater diel and seasonal stability, the coefficient of variation of each variable was calculated during the day, in each period of the year (diel cycle), and in relation to all measurements during the year (seasonal cycle). These measurements are similar to the coefficient of seasonal variation developed by ZARET (1982). The paired t-test (VIEIRA 1991) was applied to the coefficients of variation of all variables where areas or zones were compared. ANOVA (KREBS 1989) and Tukey-Krammer test were also applied to coefficients of seasonal variation of variables among areas or zones.

Principal components analysis (PCA) (DIGBY & KEMPTON 1987) was performed on the log-transformed data matrix of physical and structural variables. We considered five periods, four areas and zones, and five schedules of measurements, totaling 100 samples. A variable was considered significantly correlated with an axis when its distance d to origin was $d = \sqrt{2}/m$, where m = number of variables (LEGENDRE & LEGENDRE 1983).

Results

Table 1 shows minimum, maximum, and mean values of transparency, temperatures, dissolved oxygen and oxygen saturation (surface/bottom) in the areas/zones of Batata Lake. In the natural area/*igapó* zone, transparency of 0.50 m was reached once, and the lowest values were approximately 1.10 and 1.20 m (Fig. 3). Transparency was significantly lower in the silted area, but there was no difference between the *igapó* and limnetic zones (Anova, $p < 0.05$, Table 2). The temperature was lowest near dawn (04:00 h), and increased during the day to maxima at 13:00 h and 16:00 h (Fig. 4). The lowest temperatures were observed during the flood phase. There were no differences in surface temperature among areas or zones. However, bottom temperatures were higher within the *igapó* zone (Anova, $p < 0.05$, Table 2). In general, the dissolved oxygen concentration at surface was lower in the silted area (Fig. 5), and the lowest values were in the silted area/*igapó* zone (Anova, $p < 0.05$, Table 2). Bottom oxygen concentrations were higher in the natural area, but there were no significant differences between the *igapó* and limnetic zones (Anova, $p < 0.05$, Table 2). The results did not indicate any divergences between the *igapó* and limnetic zones. However, dissolved oxygen tended to be lower in the *igapó* zone, mainly in the silted area. Oxygen saturation at the surface was lower in the silted area/*igapó* zone, and at the bottom was higher in the natural area/limnetic zone (Anova, $p < 0.05$, Table 2, Fig. 6).

Principal components analysis (PCA) relating 11 environmental variables to the distribution of samples yielded 4 axes with eigenvalues exceeding 1.0 (accounting for 80.77 % of the variance). The first PCA axis explained 42.03 % of the variance (Fig. 7) and was positively correlated with water level and samples in the flood season, and negatively with dissolved oxygen concentration, dissolved oxygen saturation, temperature, and samples in the dry season. The intermediate and less stable character of the variables during the drawdown and filling seasons did not indicate a homogeneous pattern of sample distribution. The second axis explained 14.83 % of the variance, and was positively correlated with transparency and samples from the natural area, and negatively with bauxite tailings, bottom temperature, and samples from the silted area.

In regard to the diel variability of limnological parameters, the natural area varied less than the silted area (t-test, $p < 0.05$, Table 3). However, no significant differences between the *igapó* and limnetic zones were found (t-test, $p < 0.05$, Table 3). In relation to seasonal variability (Fig. 8), the natural area varied less than the silted area (t-test, $p < 0.05$, Table 3). The limnetic zones showed wider seasonal variation than the *igapó* zones (t-test, $p < 0.05$, Table 3). The silted area/limnetic zone was less stable than the natural area/*igapó* zone over the seasonal cycle (Anova, $p < 0.05$, Table 2).

Individual wild rice plants in the silted area had 2.66 m of submerged structure in March 2001. In March 2002, individuals had 2.21 m, against 4.72 m of submerged structure in the natural area. Therefore, wild rice stands in the silted area grew about 2.5 m taller than plants in the natural area. In wild rice banks in the silted area, the average period of flooding is 7 to 8.5 months, while in the natural area it is about 11 months. Wild rice growth was about 3.5 cm x d-1 (2002) to 4.6 cm x d-1 (2001), depending on the rate at which the water rose.

Discussion

In the natural area/limnetic zone, transparency varied considerably during the year (0.70 m-2.40 m), being lower in the dry-season phase, when winds agitate the bottom sediments. PANOSSO & KUBRUSLY (2000) also founded a positive correlation between transparency and depth in Batata Lake. According to SANTOS & FERREIRA (1999), in clearwater rivers, transparency varies between 1.10 and 4.50 m, and may be reduced to 0.80 m because the rains carry in suspended particles. Unlike Batata Lake, the transparency of the Trombetas River is lower in the flood phase (Secchi: 1.60 m), according to the data of PANOSSO (1993). The shallow depth during the dry phase (1.50 m) and the absence of currents during most of the year in Batata Lake contribute to inverse seasonal variation in transparency between river and lake. In the silted area, during the filling phase and, mainly, during the drawdown and dry phases, the transparency was similar to whitewater rivers (e.g., SANTOS & FERREIRA 1999). The effects of the reduction in transparency by suspended bauxite tailings are evident. These effects are most pronounced when the water recedes (PANOSSO & KUBRUSLY 2000). In the flood stage, the entry of a large volume of water from the Trombetas River to the lake produces uniform conditions, reducing the differences between the natural and silted areas (BOZELLI 1992, 1994).

Wider variations in temperature (26.3 °C-37.4 °C) than were recorded by PANOSSO & KUBRUSLI (2000) (28.5 °C-32.8 °C) in different areas of Batata Lake were a function of our diel measurements, which found the lowest temperatures at 04:00 h and highest between 13:00 h and 16:00 h. Bottom temperatures were higher in shallow waters, i.e., in the *igapó* (in relation to the limnetic zone) and in the silted area (in relation to the natural area). The widest variations between surface and bottom were found in the limnetic zone during the filling and drawdown periods, mainly between 13:00 h and 16:00 h, and the temperature was homogeneous at 04:00 h. These results are similar to those obtained by ESTEVES et al. (1994) during an earlier flood stage. ESTEVES et al. (1994) and PANOSSO & KUBRUSLY (2000) observed thermal gradients during the flood stage in different areas of Batata Lake, which became isothermal at night's end. These conditions do not obtain in all the lakes in the same basin; for instance, Mussurá Lake, which is located near Batata Lake, maintains a thermal gradient at night because lentic characteristics continue during the flood stage (ESTEVES et al. 1994). In the *igapó* no thermal gradients were found, probably because of the shade, which attenuates solar radiation, and the shallower water. However, in the silted area/*igapó* zone, greater differences between surface and bottom temperatures indicate a lower efficiency of the recovering *igapó* forest.

Batata Lake has higher levels of oxygen saturation than other Amazonian lacustrine systems (PANOSSO 1993). Decomposition of organic matter may be the principal factor responsible for the rapid decrease in dissolved oxygen concentration at night and especially near the bottom, coinciding with results obtained by ESTEVES et al. (1994) in Batata and Mussurá lakes, and by SANCHÉZ-BOTERO et al. (2001) in lakes of the Ati Paraná-Solimões region. During the day, higher oxygen saturation indicates phytoplankton photosynthesis. Lower oxygen contents during the flood phase are associated with flooding of terrestrial areas and with deeper water. In the silted area, greater bacterial productivity and turnover rate (ANESIO et al. 1997; ANESIO 2000), and lower phytoplankton production and density (ROLAND & ESTEVES 1998) are probably responsible for the lower oxygen concentration and saturation. ANESIO (2000) noted that suspended clay particles serve for adsorption of dissolved organic matter and a substratum for intense microbial activity. There is a tendency toward decreased oxygen concentration and saturation levels in the *igapó* zone. This was not indicated by the analysis of variance, because the variations among areas were larger. This is probably related to the decomposition of organic matter from litter, and to the higher temperatures in the *igapó*. Anoxia was almost never seen, in contrast to central Amazonian lakes which contain large amounts of decomposing macrophytes and are shaded over much of their surfaces, with consequences for the lake metabolism (e.g., JUNK et al. 1983; MELACK & FISHER 1983; SOARES et al. 1986; CRAMPTON 1999; SÁNCHEZ-BOTERO et al. 2001). The low amount or the absence of floating macrophytes, as *Eichornia crassipes*, in the Batata Lake and in others clearwater and blackwater systems are attributed to the low nutrients concentrations combined to the low pH values (JUNK & FURCH 1980). The transition of the lake hydrodynamics from lentic to lotic during flood period is another factor contributing to the high levels of dissolved oxygen observed in the Batata Lake.

The wild rice inhabits the interface between the permanently aquatic zone and the *igapó* forest, germinating during the dry season where there is direct sunlight (ENRICH-PRAST 2000). Rice is an annual rooted grass that maintains vegetative parts above the surface, following the rising water level. Standing crops of annual grasses such as *O. perennis*, *Hymenachne amplexicaulis*, and *Paspalum repens* may average 10 t x ha^{-1} (JUNK 1986). ENRICH-PRAST (2000) measured approximately 9 t x ha^{-1} of *O. glumaepatula* in the silted area of Batata Lake. Considerable seasonal losses occur during the change from the aquatic to terrestrial phases (JUNK 1986). In Batata Lake, the margins between the *igapó* and limnetic zones of the natural area are narrow and highly sloped. Thus, the wild rice occupies only a narrow zone in front of the *igapó*, where there is a longer flooding period (11 months). Deposition of bauxite tailings created a bare, gently sloped area, where there is more time and surface area for wild rice establishment, than in the natural area. Nevertheless, wild rice stands in the silted area are flooded for a similar length of time as the natural *igapó* zones, indicating that they are constrained to some degree by tree shade, and that these locations are potential *igapó* areas. Wild rice stands offer important seasonal resources for the aquatic biota, serving as cover and substratum for periphyton and invertebrates. In the silted area of Batata Lake, the establishment of extensive wild rice banks was associated with the seasonal increase in the abundance and biomass of fish, especially migratory species (LIN 2003). Therefore, wild rice banks are an important factor in seasonal variability, and are associated with the life histories of several species in the ecosystem.

The higher coefficients of variation seen in the limnetic zone suggest that the structure created by the *igapó* forest contributes to habitat stability. Basic factors associated with the greater seasonal variability in the silted area/limnetic zone were the shallower depth and direct exposure to solar radiation. The structure of the *igapó* softens variations through factors as decrease of the intensity of solar radiation and action of winds, presenting perennial structure in relation to the macrophytes banks. If the evolution in stablest habitats selects less tolerant species to the variation as a peculiar case of specialization (sensu ODUM 1971), species associated to the *igapó* could be more sensitive to artificial alterations in its habitat. The lower diel and seasonal coefficients of variation of the limnological parameters in the natural area indicate that habitat conditions are more stable there, than in the silted area. The wider variability in limnological parameters in the silted area was associated with the consequences of tailings deposition, such as shallow depth and incomplete vegetation cover.

Changes generated by bauxite tailings, such as higher temperatures, lower oxygen concentration and saturation, greater instability, and establishment of wild rice stands, are related mainly to the decrease in the transparency and raising of the bottom. The presence of extensive wild rice stands in potential *igapó* areas is another variable factor. The structure of the *igapó* attenuate sun light, softing variations of the limnological parameters. Decomposition of the litter probably contribute to the tendency of lower dissolved oxygen in the *igapó* zone. The primary-successional *igapó* forest has not attained a structure capable of maintaining more stable habitat conditions, as it has in the natural area.

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Table 1: Minimum, maximum, and mean transparency, temperatures, dissolved oxygen and oxygen saturation values (surface/bottom) in the areas/zones of Batata Lake obtained from March 2001 through March 2002. Legend: NI = natural area/*igapó* zone; NL = natural area/limnetic zone; SI = silted area/*igapó* zone; SL = silted area/limnetic zone.

Parameters	**Transparency (m)**			**Temperature (°C)**			**Dissolved oxygen (mg/l)**			**Oxygen saturation (%)**		
Localities	**Min**	**Max**	**X**	**Min**	**Max**	**X**	**Min**	**Max**	**X**	**Min**	**Max**	**X**
NI	0.50	2.20	1.44	28.8/28.5	33.4/32.4	31.0/30.5	2.93/2.47	5.50/4.17	4.32/3.46	37.5/28.5	75.2/55.4	58.0/42.6
NL	0.70	2.40	1.38	28.3/26.3	34.8/33.5	31.4/29.6	2.98/2.60	6.20/6.15	4.72/4.09	38.1/34.9	86.0/81.7	63.7/54.5
SI	0.30	1.20	0.63	26.7/26.9	35.2/33.5	31.1/30.3	2.50/2.03	4.66/3.81	3.53/2.66	30.5/23.2	66.5/49.4	47.1/37.1
SL	0.20	1.40	0.60	27.4/27.6	37.4/34.4	31.8/30.6	2.82/1.53	5.60/5.45	4.35/3.22	40.0/20.1	78.4/74.5	61.1/47.1

Table 2: F-values from one-way ANOVA and Tukey-Krammer test, testing differences among areas/regions of Batata Lake in relation to limnological parameters and their coefficients of seasonal variation, between March 2001 and March 2002. Legend: NI = natural area/*igapó* region, NL = natural area/limnetic region, SI = silted area/*igapó* region, SL = silted area/limnetic region, S = surface, B = bottom, N = sample size. Obs.: values below confronted areas correspond to calculated Q (*significant at respective p-value).

Variable	**N**	**F**	**p**	**d.f.**	**Qcritic**	**SIXNI**	**SIXSL**	**NIXNL**	**NIXSL**	**NIXNL**	**SLXNL**	**Conclusion**
Secchi	20	13.854	0.0001	3	3.745	6.21*	1.025	7.49*	5.19*	1.281	6.47*	SI<NI;SI<NL;NI>SL
T °C S	20	2.063	0.1153	3								
T °C B	20	9.572	0.0001	3	3.745	1.064	2.767	5.85*	3.83*	6.91*	3.079	SI>NL;NI>SL;NI>NL
[O$_2$] S	20	18.901	0.0001	3	3.745	8.33*	5.91*	9.91*	2.418	1.58	3.99*	SI<NI;SI<SL;SI<NL;SL<NL
[O$_2$] B	20	24.691	0.0001	3	3.745	6.99*	0.709	9.19	7.71*	2.196	9.90*	SI<NI;SI<NL;NI>SL;SL<NL
% O$_2$ S	20	16.474	0.0001	3	3.745	7.69*	7.98*	8.57*	0.287	0.88	0.593	SI<NI;SI<SL;SI<NL
% O$_2$ B	20	9.683	0.0001	3	3.745	3.11	1.378	7.17*	1.734	4.06*	5.79*	SI<NL;NI<NL;SL<NL
CVS	7	53.487	0.0001	3	3.997	1.142	14.01*	0.613	15.15*	0.528	14.63*	SI<SL;NI<SL;SL>NL

Table 3: Paired t test comparing seasonal and diel coefficients of variation in limnological parameters (transparency, temperature, dissolved oxygen concentration and saturation) between sampling sites in Batata Lake, March 2001 through March 2002. Legend: NI = natural area/*igapó* zone, NL = natural area/limnetic zone, SI = silted area/*igapó* zone, SL = silted area/limnetic zone; N = size of the sample, df = degrees of freedom; Boldface indicates significance at respective p-value.

Cycle	**Area/region**	**N**	**df**	***t***	**p**	**Conclusion**
Diel	SI x NI	28	27	2.68	0.006	SI > NI
Diel	SL x NL	42	41	2.42	0.010	SL > NL
Diel	SI x SL	28	27	0.25	0.804	SI = SL
Diel	NI x NL	28	27	0.21	0.837	NI = NL
Seasonal	SI x NI	7	6	2.07	0.042	SI > NI
Seasonal	SL x NL	7	6	8.12	0.000	SL > NL
Seasonal	SI x SL	7	6	6.26	0.000	SI < SL
Seasonal	NI x NL	7	6	2.18	0.036	NI < NL

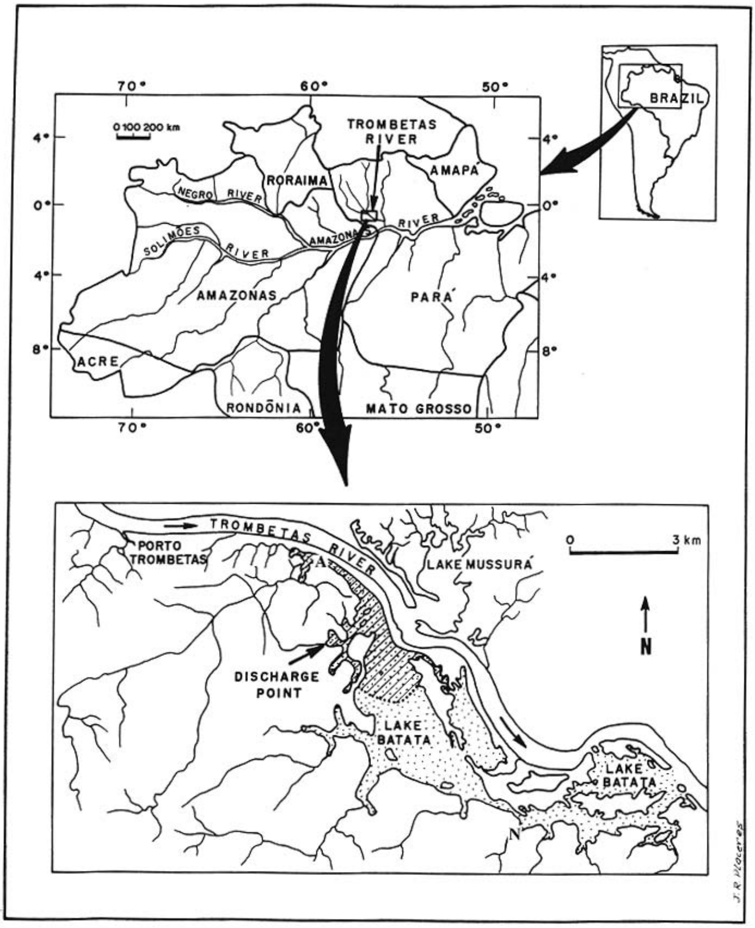


Fig. 1:
Location of Batata Lake, Porto Trombetas, state of Pará, showing the sampling areas. Legend: **A** - silted area, **N** - natural area. Map modified from the original provided by MRN.

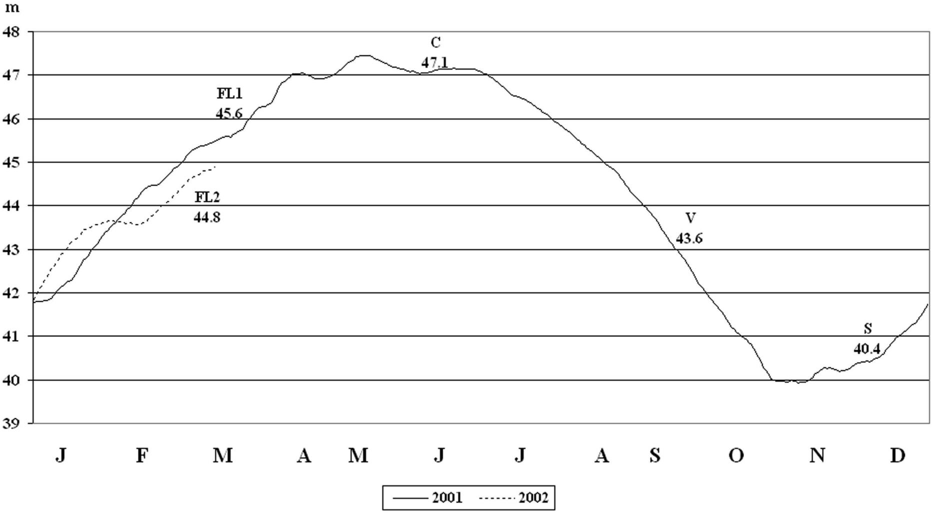


Fig. 2:
Water level of the Trombetas River in excess of 40 m above sea level from January 2001 through March 2002, showing sampling periods in Batata Lake: filling 1 (FL1), flood (FD), drawdown (DD), dry (DR), and filling 2 (FL2).

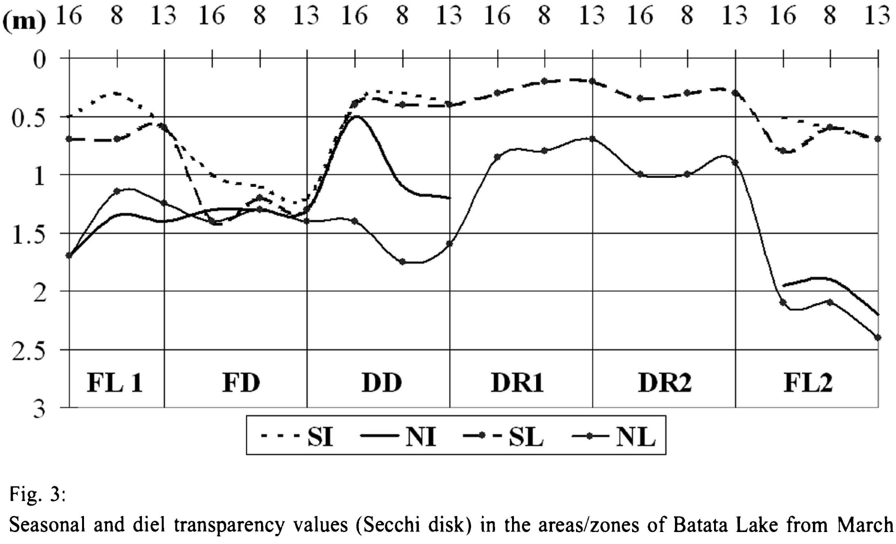
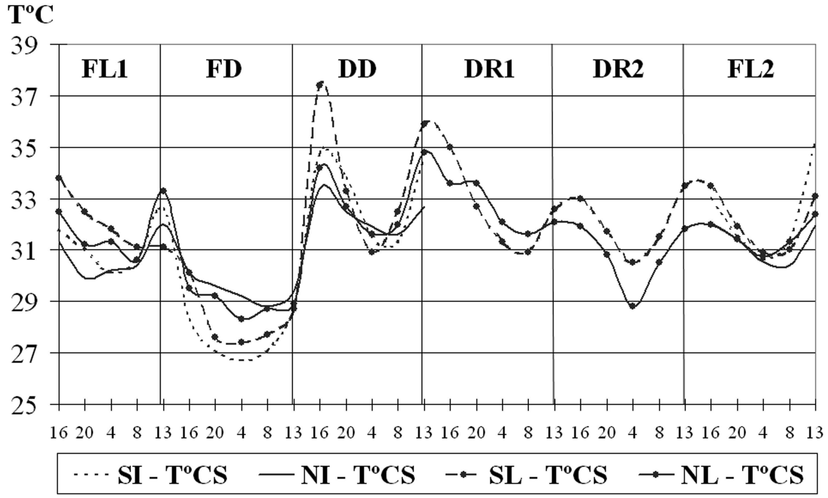


Fig. 3:
Seasonal and diel transparency values (Secchi disk) in the areas/zones of Batata Lake from March 2001 through March 2002. NI = natural area/*igapó* zone; NL = natural area/limnetic zone; SI = silted area/*igapó* zone; SL = silted area/limnetic zone; FL1 = filling 1; FD = flood; DD = drawdown; DR1 = dry 1; DR2 = dry 2; FL2 = filling 2.



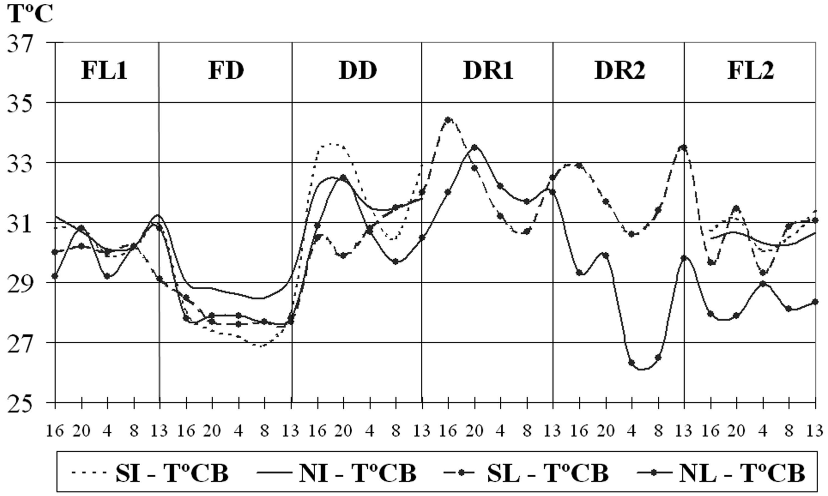
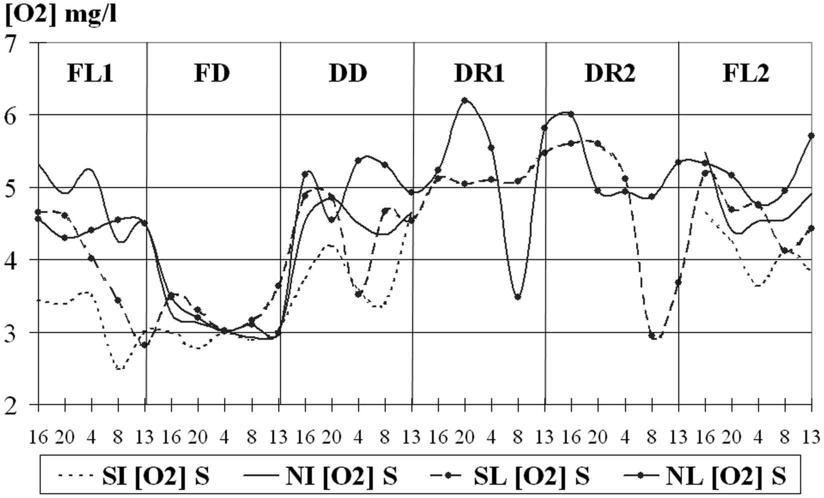


Fig. 4:
Seasonal and diel temperature values in the areas/regions of Batata Lake from March 2001 through March 2002. NI = natural area/*igapó* zone; NL = natural area/limnetic zone; SI = silted area/*igapó* zone; SL = silted area/limnetic zone; S = surface; B = bottom; FL1 = filling 1; FD = flood; DD = drawdown; DR1 = dry 1; DR2 = dry 2; FL2 = filling 2.



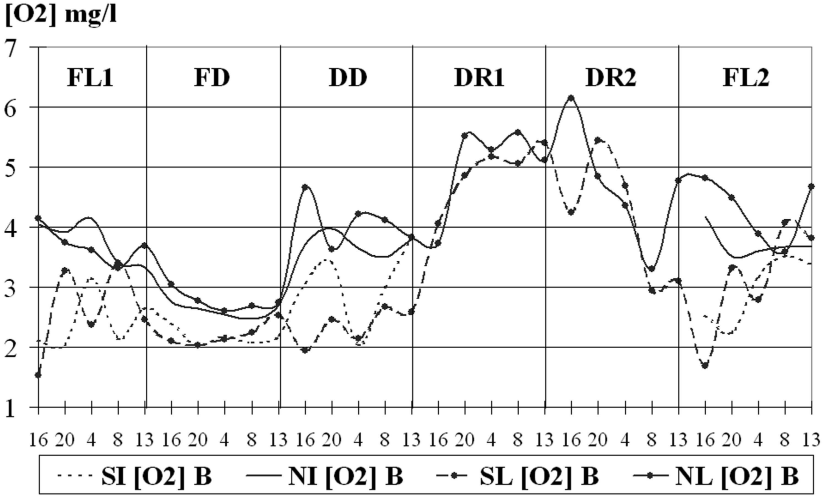


Fig. 5:
Seasonal and diel dissolved oxygen concentrations in the areas/zones of Batata Lake from March 2001 through March 2002. NI = natural area/*igapó* zone; NL = natural area/limnetic zone; SI = silted area/*igapó* zone; SL = silted area/limnetic zone; S = surface; B = bottom; FL1 = filling 1; FD = flood; DD = drawdown; DR1 = dry 1; DR2 = dry 2; FL2 = filling 2.

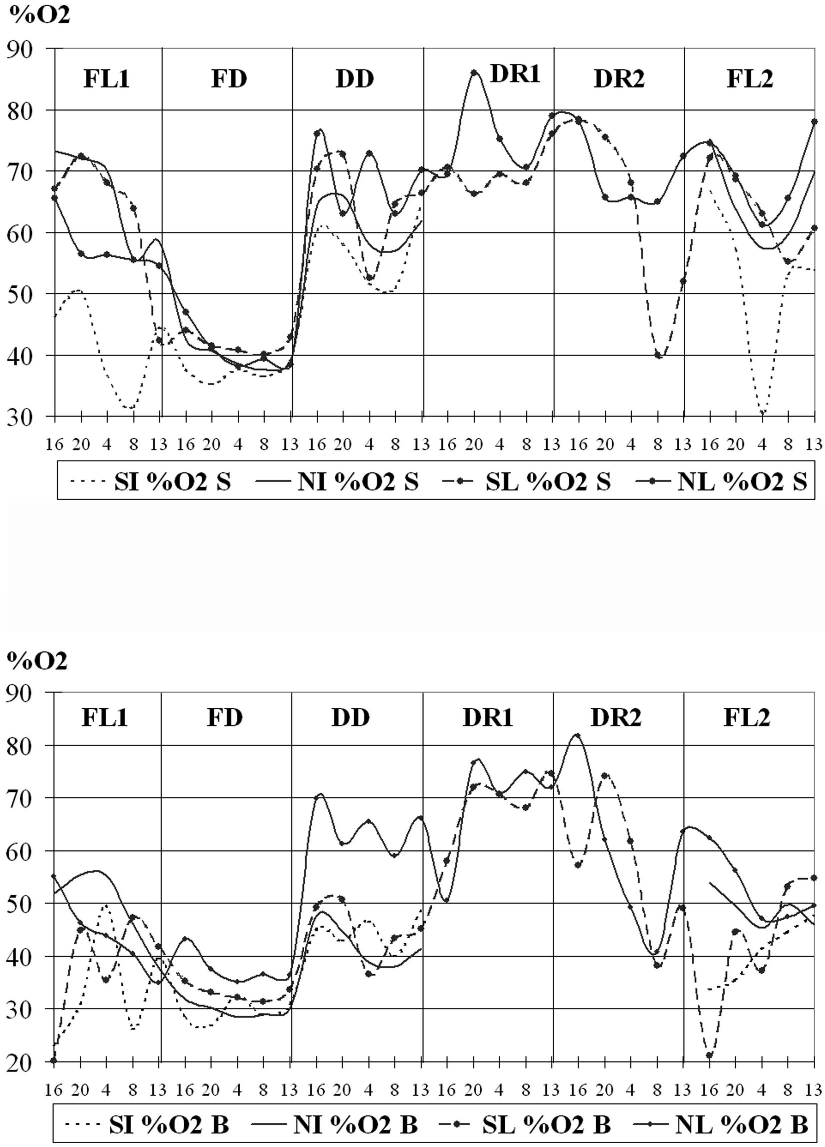


Fig. 6:

Seasonal and diel percentages of oxygen saturation in the areas/zones of Batata Lake from March 2001 through March 2002. NI = natural area/*igapó* zone; NL = natural area/limnetic zone; SI = silted area/*igapó* zone; SL = silted area/limnetic zone; S = surface; B = bottom; FL1 = filling 1; FD = flood; DD = drawdown; DR1 = dry 1; DR2 = dry 2; FL2 = filling 2.

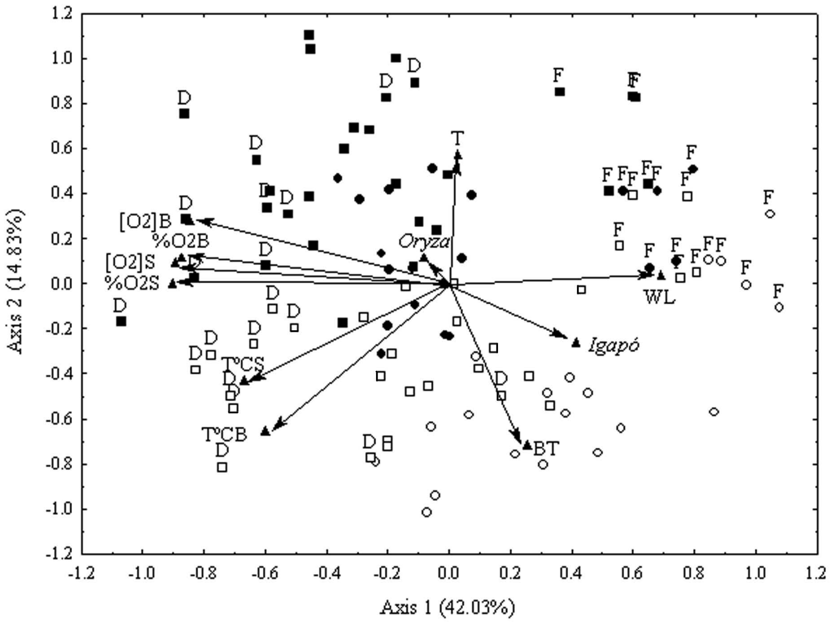


Fig. 7:

Factor loads and sample date scores on the first two PCA components for environmental parameters in Batata Lake, March 2001 through March 2002. Environmental parameters: T = transparency; $[O_2]$ = dissolved oxygen concentration; % O_2 = dissolved oxygen saturation; T ˚C = temperature; S = surface; B = bottom; WL = water level; IG = *igapó* forest; BT = bauxite tailings; *Oryza* = wild rice banks. Areas/-zones: ● natural area/*igapó* zone; (○ silted area/*igapó* zone; ■ natural area/limnetic zone; (☐ silted area/limnetic zone. Periods: F = flood; D = dry.

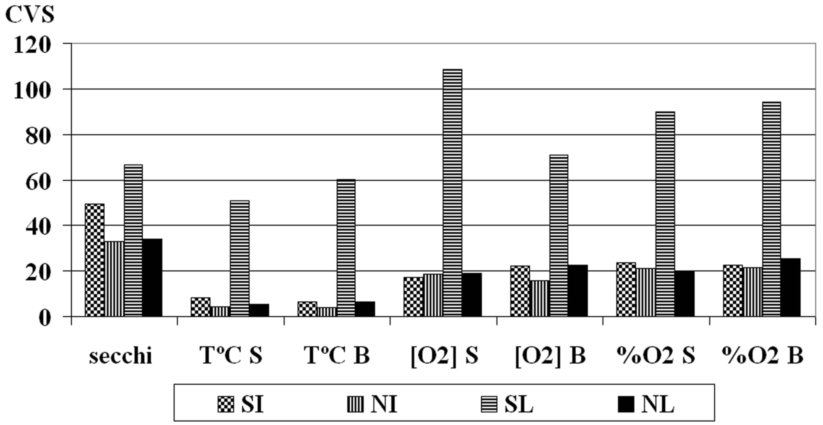


Fig. 8:

Coefficients of seasonal variation (CVS) of the water transparency (Secchi), temperature (T ˚C), dissolved oxygen concentration ($[O_2]$) and dissolved oxygen saturation (% O_2) in the areas/zones of Batata Lake from March 2001 through March 2002. NI = natural area/*igapó* zone, NL = natural area/limnetic zone, SI = silted area/*igapó* zone, SL = silted area/limnetic zone, S = surface, B = bottom.