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Long-term changes in the density of the copepod community in an Amazonian lake impacted by bauxite tailings

by

L.S. Carneiro, R.L. Bozelli & F.A. Esteves

M.Sc. Luciana S. Carneiro, Prof. Dr. Reinaldo L. Bozelli, Prof. Dr. Francisco A. Esteves, Laboratório de Limnologia, Departamento de Ecologia, Instituto de Biologia, CCS, Universidade Federal do Rio de Janeiro (UFRJ), Cidade Universitária, Ilha do Fundão, 21.941-540 Rio de Janeiro/RJ, Brazil; e-mail: lucca@biologia.ufrj.br; bozelli @biologia.ufrj.br; festeves@biologia.ufrj.br
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Abstract

We analyzed the response of the copepod community in relation to the influx of large amounts of clay from a bauxite processing operation, and to flood-pulse variations in Lake Batata, a typical Amazonian floodplain lake. From 1990 to 1999, zooplankton density and other environmental data were collected trimonthly in a natural area and in an area of the lake covered by bauxite tailings. The seasonal cycles of the main species of the orders Calanoida and Cyclopoida were closely linked to variations in the water level. Suspended clay particles may influence the top-down and bottom-up mechanisms regulating the copepod populations in Lake Batata.
Keywords: **Zooplankton, copepods, Amazonian floodplain, water level fluctuation, bauxite tailings, inorganic turbidity**.

Resumo

Foi analisada a resposta da comunidade de copépodos em relação ao lançamento de grandes quantidades de argila proveniente do processo de beneficiamento da bauxita, e ao pulso hidrológico no Lago Batata, um lago típico de planície de inundação amazônica. De 1990 a 1999, foram coletadas trimestralmente amostras de zooplâncton e algumas variáveis ambientais em duas estações do lago, uma natural e outra impactada por rejeito de bauxita. Os ciclos sazonais das principais espécies das ordens Calanoida e Cyclopoida mostraram-se fortemente correlacionados às variações do nível d'água. As partículas de argila em suspensão podem estar influenciando os mecanismos de regulação "top-down" e "bottom-up" das populações de copépodos do Lago Batata.

Introduction

Long-term studies of the temporal dynamics of zooplankton populations are common in temperate environments, and have shown that most taxonomic groups of zooplankton have clear and recurring seasonal patterns (PINTO-COELHO 1998). Equivalent studies in tropical lakes are rare (HART 1986; GARRIDO & BOZELLI 1997; PINTO-COELHO 1998), but have shown that regular seasonal fluctuations are also characteristic of tropical zooplankton populations, in spite of the greater climatic

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stability (BRANDORFF 1977; TWOMBLY 1983).

Several hypotheses have been proposed to explain changes in the structures of these tropical zooplankton populations. In the Amazon region, a number of studies have shown that the seasonal hydrological flood pulse of the system is one of the main factors controlling seasonal fluctuations in populations. A relationship between the increases in population density and the low-water period was observed in several Amazonian lakes. Populations have also been observed to decline during high-water periods, possibly because of the effect of dilution from flooding (BRANDORFF & ANDRADE 1978; ROBERTSON & HARDY 1984; BOZELLI 1994).

However, other mechanisms may contribute to seasonal changes in zooplankton community structure: food availability, predation, competition, and abiotic factors (BROOKS & DODSON 1965; SAUNDERS & LEWIS 1988; TWOMBLY 1994). Among abiotic factors, an increase in suspended inorganic material in the water column appears to be an important factor controlling zooplankton populations (BOZELLI 1996). A number of studies have demonstrated the influence of suspended inorganic material on the ecology of zooplankton, principally by changing the bottom-up and top-down regulation of populations (ARRUDA et al. 1983; HART 1984, 1986, 1987; BOZELLI 1998a, b).

Suspended clay particles may change bottom-up regulation by weakening the trophic interaction between grazing crustaceans and phytoplankton, both by limiting light and by algal-clay-floc sedimentation (PAGGI & JOSÉ DE PAGGI 1974; AVNIMELECH et al. 1982; CUKER 1987; SØBALLE & THRELKELD 1988). This may result in a reduction in the availability of phytoplankton to the zooplankton. Suspended clays may also adversely affect the filtering mechanisms of some zooplankton species, by decreasing filtering rates and the efficiency of food assimilation (PAGGI & JOSÉ DE PAGGI 1974; ARRUDA et al. 1983; HART 1988; BOZELLI 1994, 1998a, b). Conversely, clays may also adsorb dissolved organic compounds and become an important alternative food resource (AVNIMELECH et al. 1982; ARRUDA et al. 1983).

As an example of changes in zooplankton populations due to top-down regulation, turbidity may reduce the ability of a visual predator to find its prey, thus reducing the exposure of zooplankton to predation (VINYARD & O'BRIEN 1976; GEDDES 1984).

Considering the scope of possible interferences, studies on turbidity in aquatic environments are essential, because problems with human impacts acting to increase turbidity are becoming more common. Lake Batata is a typical example of human intervention: the dumping of bauxite tailings, among other impacts, increased the water turbidity. Aiming at to investigate the effects of this impact on the dynamics of the copepod populations in the lake, we analyzed data collected over a 10-year period. This sampling effort intended to observe the effects of the annual cycling of the water level on the limnological variables, and the presence of the bauxite tailings, which at certain times is responsible for intense changes in the water column.

Study Area

Lake Batata is a clear-water Amazon lake (SIOLI 1950). The lake is situated between 1°25'-1°35'S, 56°15'-56°25'W in the state of Pará, Brazil, in the hydrographic basin of the Trombetas River (Fig. 1). It remains permanently connected to the river, even during low-water periods.

One of the main characteristics of Lake Batata is a seasonal fluctuation in its water level. Changes in the physical, chemical and biotic environment are driven mainly by this hydrological periodicity. The mean depth varies between 1.25 m and 10.0 m during low water and flood, respectively. The lake surface area also changes dramatically, from 18.0 km^2 at low water to 30.0 km^2 during the flood stage (PANOSSO 1993).

Lake Batata is surrounded by vegetation termed seasonal *igapó*, because it undergoes periodic inundation. Much of the organic carbon entering Lake Batata originates in the flooded *igapó* forest.

For ten years (1979-1989), Lake Batata received 18 x 10^6 m^3/y of tailings resulting from bauxite processing. These tailings eventually covered approximately 30 % of the area of the lake bottom. The tailings are fine clay particles in the size range of 0.5 µm to 20.0 µm. The tailings form a layer a few centimeters to several meters thick over the impacted part of the lake bottom. Natural events, such as the annual periods of heavy rain, wind action, and low water level resuspend the particles and increase turbidity, mainly in the impacted part of the lake.

Material and methods

Samples were collected every three months from March 1990 through December 1999. The sampling interval corresponded to four characteristic periods of the regional flood pulse (filling, flood, drawdown, and low water). Two sampling stations were established: one station in a natural, unimpacted area of the lake, and the other in an area where the bottom was covered with bauxite tailings.

The following environmental variables were also measured: water depth, water temperature (FAC 400 electronic thermometer), water transparency (SECCHI disk), and pH (Digimed analyzer). Suspended material was determined by gravimetry. Dissolved oxygen was estimated using the WINKLER method, as modified by GOLTERMAN et al. (1978). Chlorophyll-*a* was determined after filtering the water through GF/C membranes (GOLTERMAN et al. 1978).

Zooplankton samples were taken by vertical hauls through the entire water column using a conical plankton net (68 µm mesh size). The material collected was concentrated and fixed in a 4 % sugar-formaldehyde solution. Copepods were counted in subsamples of 1.0 to 10.0 ml. At least 250 individuals and no fewer than three subsamples were counted per sample. Samples with few individuals were counted completely.

A Principal Component Analysis (PCA) was performed using the Windows version of the PC-ORD package (Version 4.0), to examine spatial and temporal variation in the copepod assemblage, and to determine the importance of environmental variables in structuring this assemblage. For the PCA analyses, the results of organism density were presented as percentages, in order to minimize the effects of the large differences in water depth between stations and season of sampling.

Results

Temperature, pH, dissolved oxygen, and water depth

Seasonal changes in temperature (Fig. 2a), dissolved oxygen (Fig. 2b), pH (Fig. 2c), and water depth (Fig. 2d) varied similarly in the natural and impacted areas. The highest water temperatures and levels of dissolved oxygen were observed during drawdown and low-water periods, when shallower water allowed more light penetration, more wind mixing, and more intense phytoplanktonic activity. The pH was similar in the two areas, ranged from 4.8 to 6.7, and showed no seasonal trends. Water depth fluctuated dramatically, but similarly in the natural and impacted areas. During the 10-year period, depths ranged from 1.7 m to 7.7 m in the natural area, and from 0.75 m to 6.5 m in the impacted area. There were no significant differences ($p > 0.05$) between the natural and impacted areas of the lake, for any of these variables.

Water transparency, suspended material, and chlorophyll-*a*

Environmental variables more likely to effect copepod density in Lake Batata are water transparency (Fig. 2e), suspended solids (Fig. 2f), and chlorophyll-*a* (Fig. 2g). Secchi disk readings are generally inversely related to the amount of suspended solids. This inverse relationship was clearly apparent during the sampling years 1991, 1994, 1995, 1997, and 1999. Secchi depth readings of nearly 0 to 0.5 m corresponded to large amounts of suspended solids in the water column, especially in the impacted area. Figures 2d and 2e also show that water transparency increased during filling and flooding. Turbidity was high and water transparency was low during drawdown and low-water periods, when suspended solids became concentrated in the shallower water. During these periods, Secchi disk readings were never greater than 0.7 m, and concentrations of suspended solids reached 92.8 mg/l. The mean concentration of chlorophyll-*a* (Fig. 2g) in the natural area was 5.23 mg/l, and levels usually increased during the low-water periods. The mean value of chlorophyll-*a* in the impacted area was 4.18 mg/l. Chlorophyll-*a* increased when water levels were low, light penetration was high, and nutrients were concentrated in the water.

Copepod Community

Cyclopoid copepods were represented almost exclusively by the dominant and continuously present *Oithona amazonica* BURCKHARDT. This species occurred in relatively high densities in both areas (Fig. 3a, b). It had a clear and recurring seasonal cycle, reaching maximum density during low water, up to 31,582 ind/m^3.

Calanoid copepods were represented by three species. *Notodiaptomus coniferoides* WRIGHT was found in both areas; it reached maximum densities during low water, up to 17,660 ind/m^3. Its populations also appeared to fluctuate with the hydrological pulse, nearly disappearing during the flood period (Fig. 3a, b). *Aspinus acicularis* BRANDORFF also found in both areas, followed a similar pattern (Fig. 3a, b). Its maximum densities never exceeded 4,500 ind/m^3 during low water. *Rhacodiaptomus retroflexus* BRANDORFF occurred in relatively low densities, reaching a maximum of 339 ind/m^3 during low water in 1995. The density of *R. retroflexus* did not appear to fluctuate with the flood pulse. This species occurred more frequently in the impacted area, in limited and non-recurring periods (Fig. 3a, b).

Principal Component Analysis (PCA)

To further clarify the relationship between the zooplankton populations and the physical and chemical characteristics of Lake Batata, we used Principal Component Analysis. The following variables were taken into account: transparency (SECCHI disk), suspended material, chlorophyll-*a*, temperature, pH, dissolved oxygen, and depth, as well as the relative densities of the four species of copepods identified. The first two PCA axes were used (Table 1). These two axes accounted for 43.6 % of the total variation of the data.

The variables of transparency, depth, suspended material, chlorophyll-*a*, dissolved oxygen, and temperature explained much of the composition of axis 1 (Fig. 4a). The distribution patterns of these abiotic variables on axis 1 showed transparency and depth as a group inversely correlated with temperature, suspended material, chlorophyll-*a*, and dissolved oxygen. This pattern occurred because the water became most transparent during flood periods. During flooding, less sediment is resuspended and a large volume of water dilutes Lake Batata. During drawdown, the lake becomes shallower and wind resuspends the sediments; at this time, an increase in the phytoplankton also contributes to increased turbidity. During low water, disturbance of the water column by winds oxygenates and more evenly heats the water.

The relative densities of the copepods were clearly distributed along axis 2 (Fig. 4b). Axis 2 spatially separated the stations, which differed between the impacted and natural areas. Note that the impacted area is plotted in the negative quadrant of axis 2, where the higher relative densities of *N. coniferoides* and *R. retroflexus* are found. The natural area is plotted in the positive quadrant of axis 2, where the higher densities of *O. amazonica* are found. Analyzing the copepod community from the PCA perspective, we notice that the dynamics of this group was not only related to the fluctuations in the water level, as suggested by analysis of the absolute density (Fig. 3a, b).

Oithona amazonica was the dominant species in the copepod community, with a mean relative density of 75.8 % (Fig. 3c, d). Its highest relative densities were recorded in the natural area, during the flood stage, when it was sometimes the only species recorded.

The second most important species, in terms of percentage, was *Notodiaptomus coniferoides*, with a mean of 14.3 % (Fig. 3c, d). Its highest relative densities were recorded in the impacted area, although the differences between the two areas were not significant ($p = 0.20$). The fluctuations in both absolute and relative density of this species were strongly related to fluctuations in water level: it peaked in the drawdown period, and almost disappeared during the flood.

Although not clearly shown in the PCA (see below), *Aspinus acicularis* had significantly higher relative densities in the impacted area (7.8 %) compared to the natural area (4.6 %) ($p < 0.05$). There were no detectable seasonal changes in its relative density, possibly explaining its position in the PCA, close to zero (Fig. 4a).

Rhacodiaptomus retroflexus comprised only 3.7 % of total copepod numbers. Although no significant difference was detected ($p=0.078$), *R. retroflexus* was more frequently found in the impacted area, and reached higher densities in some flood periods. However, its occurrence was limited and non-recurrent.

Discussion

In Lake Batata, four factors seem to be paramount in explaining the seasonal dynamics of the copepod populations. The most important was the hydrological pulse. *Oithona amazonica*, *N. coniferoides*, and *A. acicularis* showed seasonal cycles linked to the changes in water level (Fig. 3a, b). These species reached their peak densities during low water, and their lowest densities during high water. Low densities of zooplankton during high water may also be a response of the copepod populations to changes in the phytoplankton community. Phytoplankton communities have their lowest densities during periods of high water, and also undergo a clear change in the composition of dominant species (HUSZAR & REYNOLDS 1997; MELO & HUSZAR 2000). Other workers have observed similar relationships between water level and zooplankton density (BRANDORFF & ANDRADE 1978; ROBERTSON & HARDY 1984).

Rhacodiaptomus retroflexus was the only species whose variation is apparently not linked to the flood pulse. It was found in significantly higher densities in the impacted area of the lake.

Fluctuations in temperature, pH, dissolved oxygen and chlorophyll-*a* affected the copepod community only minimally. The results of the PCA showed that only *N. coniferoides* appeared to be affected by environmental factors other than the flood pulse. However, during the low-water period, *N. coniferoides* became dominant in response to the shallow water, increased dissolved oxygen, higher temperatures, and a large phytoplankton population (chlorophyll-*a*). The relationship between the density of *N. coniferoides* and the concentrations of chlorophyll-*a* was especially strong. Apparently *N. coniferoides* is using phytoplankton as its main food resource. However, its highest relative densities occurred in the impacted area, where the phytoplankton biomass and chlorophyll-*a* content are significantly lower (HUSZAR 1994). This increase suggests that this species might be using another food resource at that time of year.

Neither PCA nor examination of direct correlations between the abundance of each species and chlorophyll-*a* indicated any regulation of the seasonal patterns of *O. amazonica*, *A. acicularis*, and *R. retroflexus* by changes in the availability of food. The lack of information on the feeding habits of these species could explain this lack of results. It is known that the phytoplankton alone cannot fulfill the energy requirements of natural zooplankton populations (NAUWERCK 1963). Especially copepods may feed not only on phytoplankton but also on a variety of other items such as bacteria, protozoans, rotifers, and detritus (EDMONDSON 1957), which were not examined in this study.

Suspended material may adsorb organic components and become an important food resource for zooplankton (HART 1980; AVNIMELECH et al. 1982; ARRUDA et al. 1983). Clays may be a favorable substrate for the colonization and growth of bacteria, forming aggregates of an appropriate size for consumption by zooplankton (LIND & DÁVALOS-LIND 1991). In Lake Batata, the productivity of attached bacteria is greater in the impacted area, where more clay is suspended in the water column (ANESIO et al. 1996). This alternative food resource may explain the higher densities of *N. coniferoides*, *A. acicularis*, and *R. retroflexus* in the impacted area. This may result in a significant change in the trophic structure of the food chain, which is probably based not on the carbon produced autotrophically (through phytoplankton), but on the carbon originated from bacterial (heterotrophic) activity (ANESIO et al. 1996). This seems a possible mechanism through which the suspended clays could influence the "bottom-up" regulation mechanisms of species abundance.

The dominance of *O. amazonica* may be related to its greater tolerance to the physical, chemical, and biological conditions in Lake Batata. Its permanent presence in the lake may be related to its omnivorous habit and to the raptorial behavior of cyclopoids (DUSSART & DEFAYE 1995), allowing them to selectively exploit alternative food resources, and so making them less dependent on the varying availability of algal food. Its peaks of relative density in the periods of high water, when it was sometimes the only species recorded in the lake, are probably related to the almost complete absence of competition with the other species. Its active searching behavior may increase its chances of locating food during periods of scarcity.

Predation is another mechanism controlling fluctuations in zooplankton densities (BROOKS & DODSON 1965; ZARET 1980; GLIWICZ & PIJANOWSKA 1989), and may be influenced by turbidity (HART 1988). According to several studies, suspended clays may provide shelter from visual predators (VINYARD & O'BRIEN 1976; GEDDES 1984; HART 1986). Possibly, predation on *N. coniferoides*, *A. acicularis*, and *R. retroflexus* is lower and may account for the higher standing stock of these species in the impacted area. The numbers and diversity of fish are lower in the impacted area of Lake Batata (HALBOTH 1995; REIS 1997), suggesting that predation intensity is lower in that part of the lake.

The constant presence of *O. amazonica* in Lake Batata may be a result of its ability to withstand losses by predation through recruitment of pre-adult stages, which according to SAUNDERS & LEWIS (1988), are less vulnerable to predation. Also, both the typical "hop and sink" swimming action of cyclopoids, and the fact that *O. amazonica* is the smallest copepod species in Lake Batata may reduce visual predation of this species and allow it to dominate in the lake.

Conclusion

We conclude that the suspended material influences the top-down and bottom-up mechanisms of regulation of the copepod populations in Lake Batata. In regard to top-down regulation, the bauxite tailings suspended in the water column may be hampering the visual predators. As for bottom-up regulation, the clays apparently change the trophic structure in the lake, since in spite of reducing the stocks of phytoplankton and interfering with the filtering mechanisms of some species of microcrustaceans (BOZELLI 1998b) they may be an important food resource for the zooplankton.

The results of this study suggest that the presence of suspended material in the water of Lake Batata alters the dynamics of the copepod community. However, this change is not constant. The impact of the bauxite tailings may be magnified by the fluctuations in water level caused by the hydrological regime. The clays that compose the tailings are easily resuspended during the drawdown and low-water periods, because of the shallow depth and strong currents and winds. At those times of year, the two areas are completely different and the turbidity may significantly affect the copepod community. However, the flood pulse seems to be the dominant force structuring this environment.

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Table 1: Eigenvalues and percentage of total variance explained by the first two axis of Principal Component Analysis (PCA) based on zooplankton organisms and major physico-chemical characteristics of Lake Batata.

Axis	**Eigenvalue**	**% of Variance**	**Cumulative % of Variance**
1	2,978	27,069	27,069
2	1,818	16,528	43,597

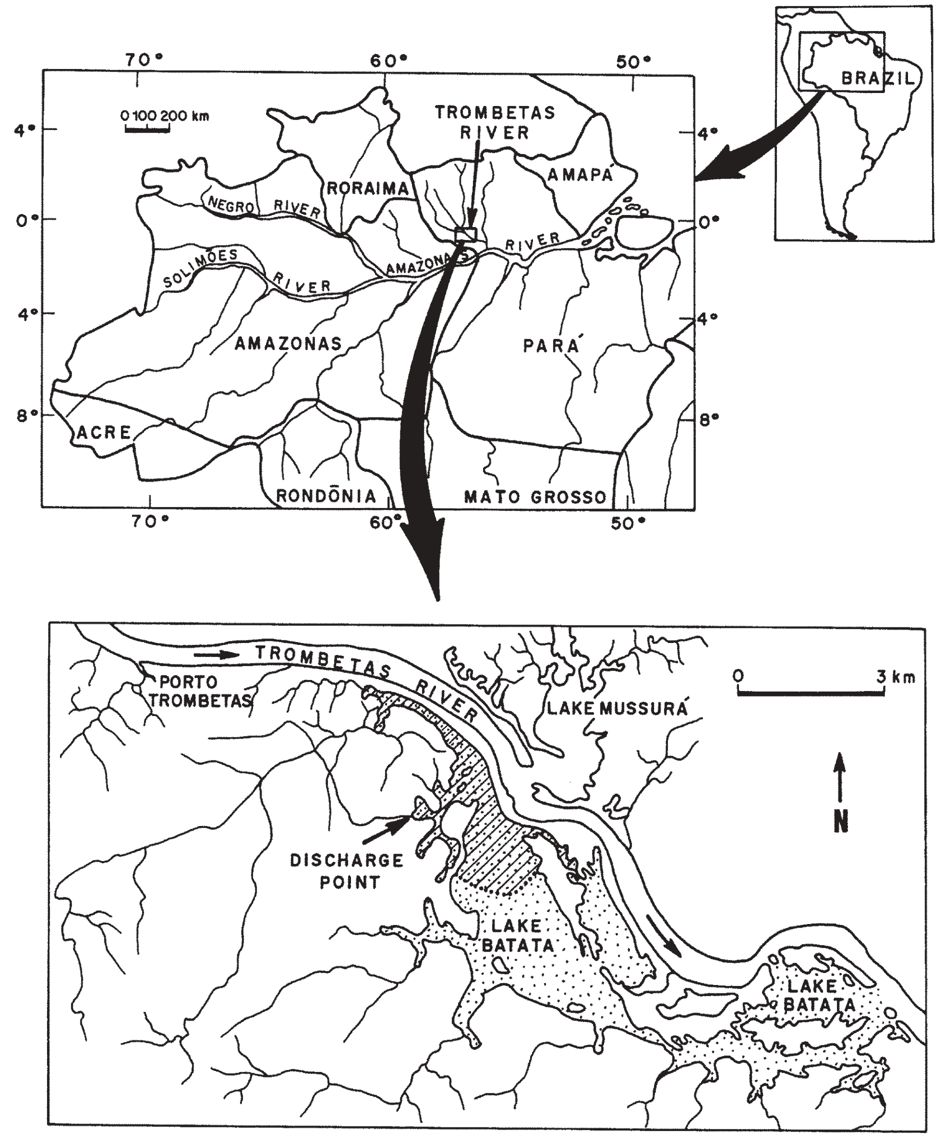

Fig. 1:
Map of geographic localization of Lake Batata.

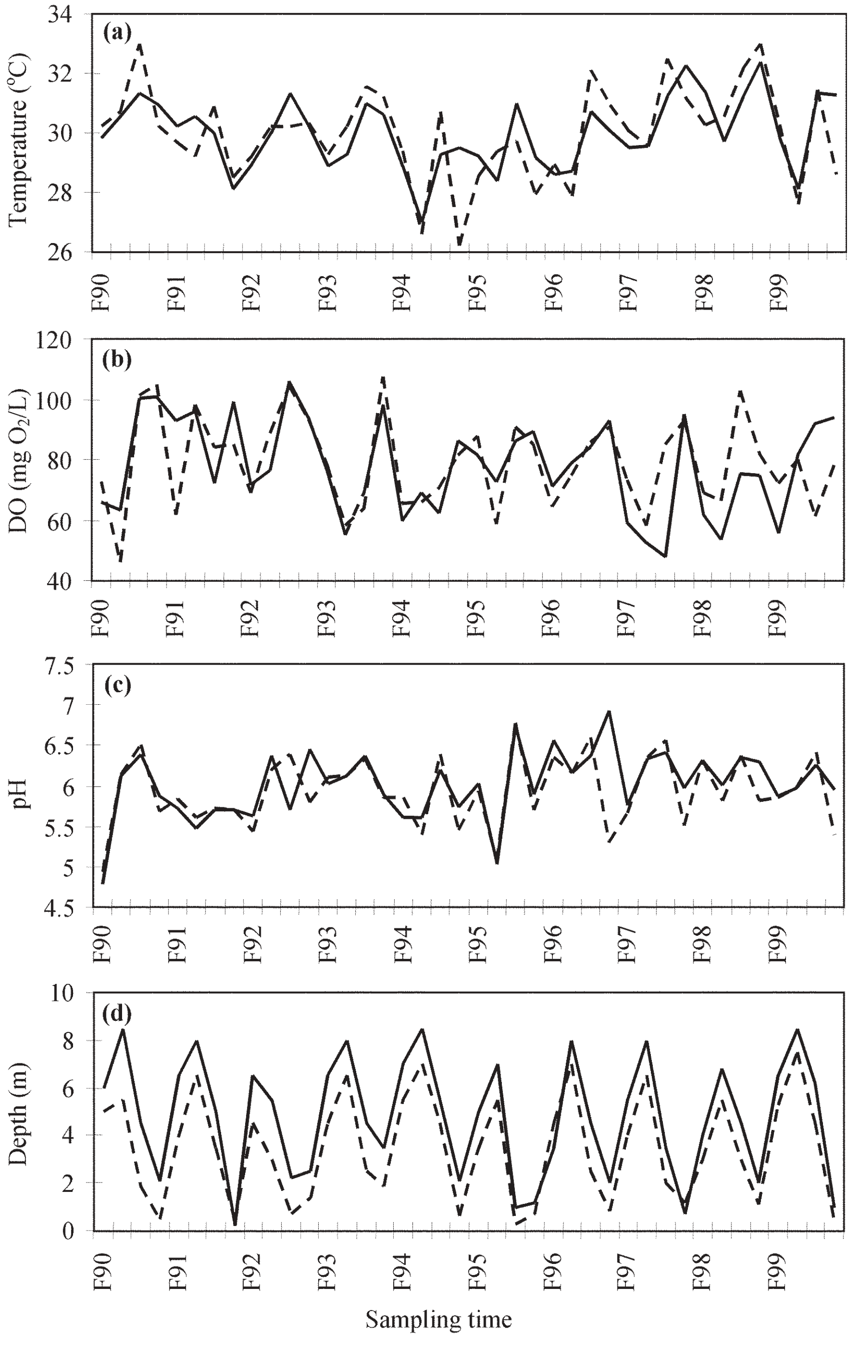

Fig. 2:
Temporal variation of temperature (**a**), dissolved oxygen (**b**), pH (**c**), water depth (**d**) in natural (—) and impact (---) area. (Letter F on the sampling time axis means FILLING).

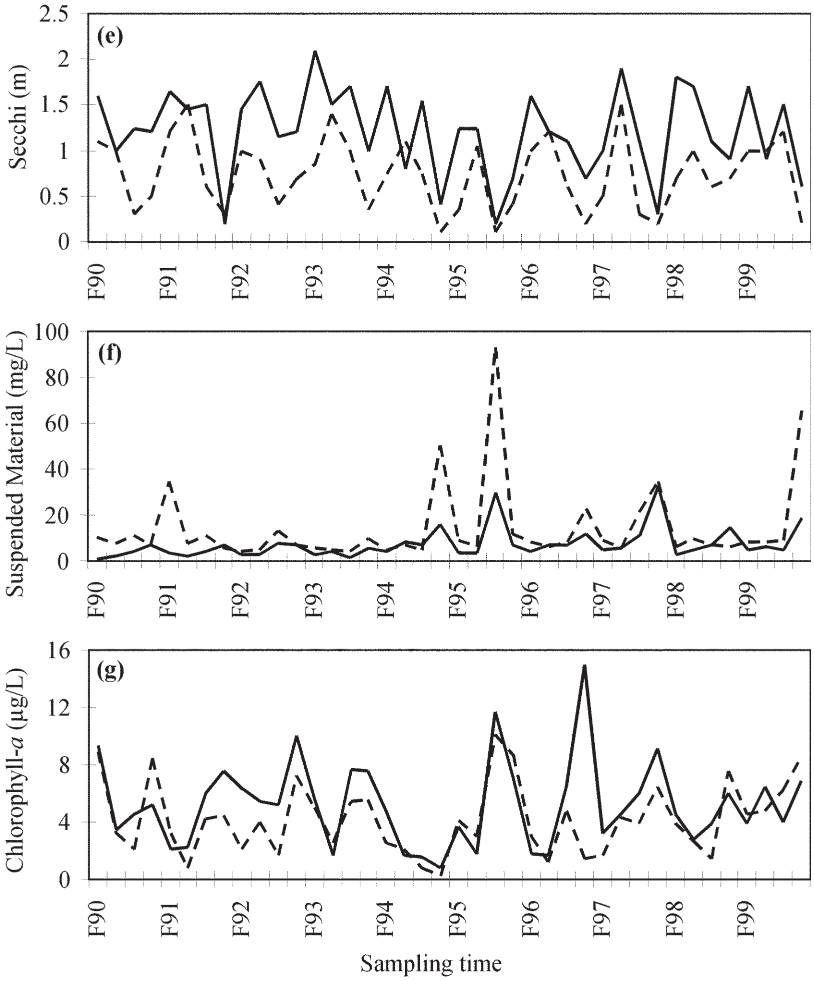

Fig. 2: Continuation.
Temporal variation of SECCHI disk (**e**), suspended material (**f**), and chlorophyll-*a* (**g**) in natural (–) and impacted (---) area. (Letter F on the sampling time axis means FILLING).

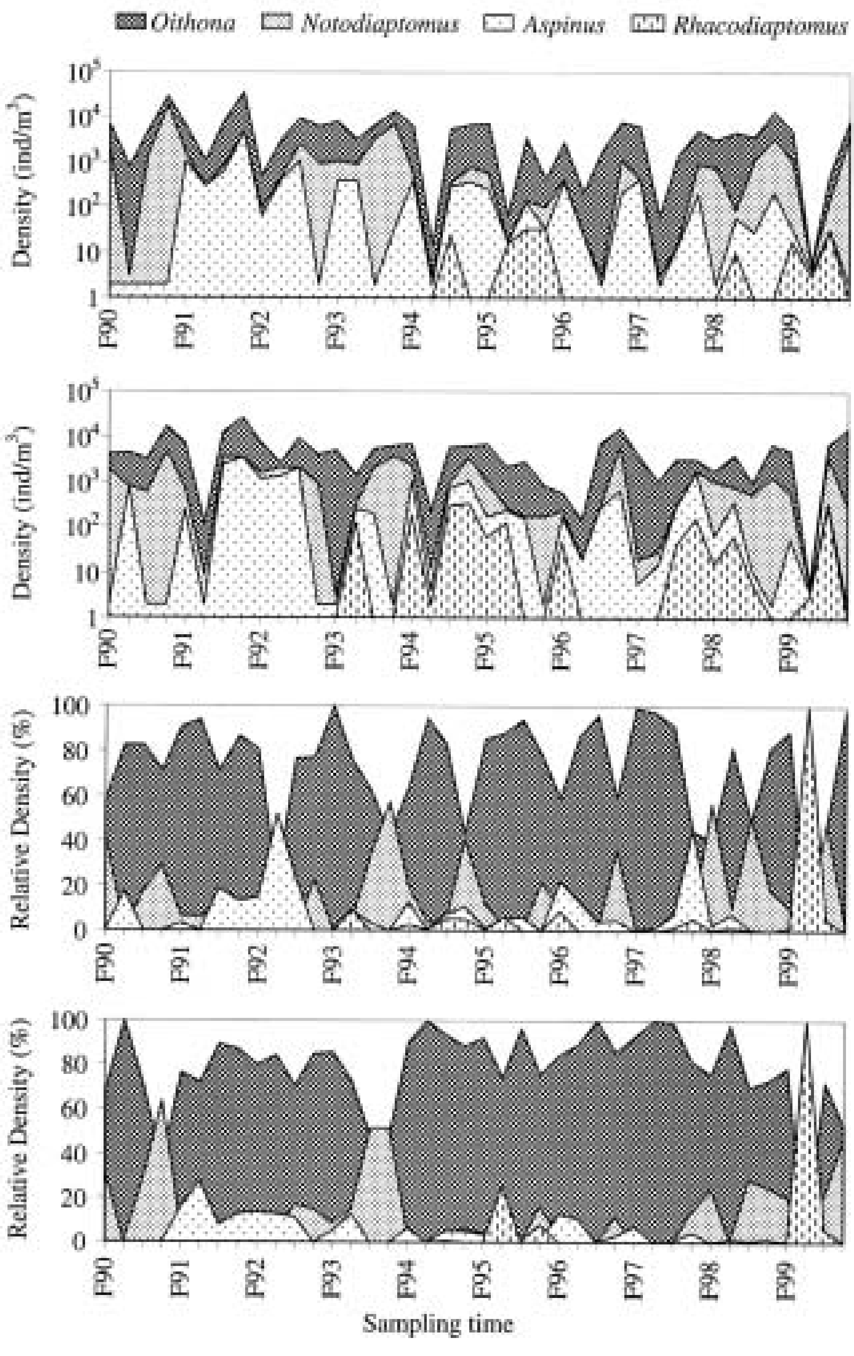

Fig. 3:
Temporal variation of absolute density of copepods species in natural (**a**) and impacted (**b**) area. Temporal variation of relative density of copepods species in natural (**c**) and impacted (**d**) area (***Oithona***, *O. amazonica*; ***Aspinus***, *A. acicularis*, ***Notodiaptomus***, *N. coniferoides*; ***Rhacodiaptomus***, *R. retroflexus*). (Letter F on the sampling time axis means FILLING).

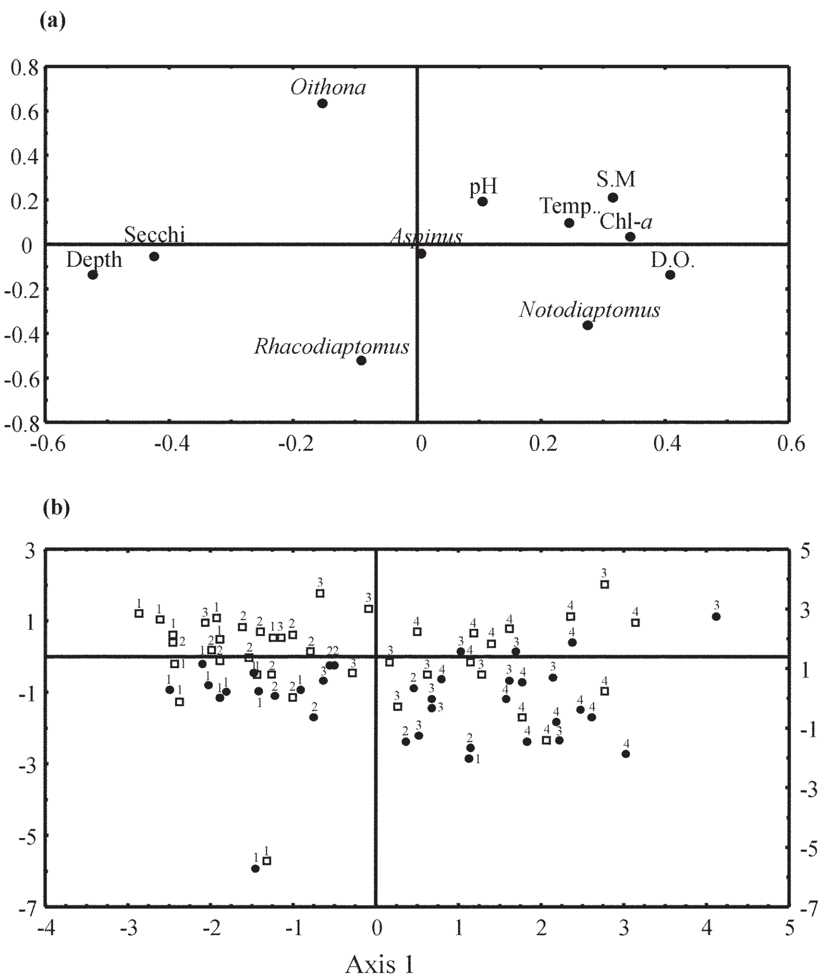

Fig. 4:

Principal Component Analysis (PCA) plot axis 1 vs. 2. Variables graph (top) and samples graph (bottom). (**Secchi**, SECCHI disk; **Depth**; **pH**; **Temp.**, temperature; **S.M.**, suspended material; **Chl-*a***, chlorophyll-*a*; **D.O.**, dissolved oxygen; ***Oithona***, *O. amazonica*; ***Aspinus***, *A. acicularis*, ***Notodiaptomus***, *N. coniferoides*; ***Rhacodiaptomus***, *R. retroflexus*; **1**: flood; **2**: filling; **3**: drawdown; **4**: low water; □ natural area; ● impacted area).