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Effect of *Campsurus notatus* on NH_4^+ , DOC Fluxes, O_2 Uptake and Bacterioplankton Production in Experimental Microcosms with Sediment-Water Interface of an Amazonian Lake Impacted by Bauxite Tailings

key words: bioturbation, bacterioplankton, bauxite tailings, Amazonian lake

Abstract

The aim of this study was to evaluate the influence of *Campsurus notatus* EATON 1868 (Ephemeroptera: Polimitarcyidae) and the impact of bauxite tailings on ammonium (NH_4^+) and dissolved organic carbon (DOC) fluxes, oxygen uptake and bacterioplankton production in the sediment-water interface of Lake Batata, a shallow Amazonian floodplain lake. Mesocosms were constructed from natural and impacted areas of Lake Batata, to reproduce the sediment-water interface. The cores were incubated with 0 to 2,388 ind m^{-2} of *Campsurus notatus* nymphs, and the changes in NH_4^+ , DOC, O_2 concentration and bacterioplankton production in the overlying water column were measured. Ammonium efflux ($F = 9.8$, $p < 0.05$, multiple regression) and oxygen uptake ($F = 11.8$, $p < 0.05$) showed a significant correlation with the density of *C. notatus* in the cores with natural sediment. No differences on DOC release were observed in cores with natural or impacted sediment. In the cores incubated with natural sediment and nymphs of *C. notatus*, a significant increase (Two-way ANOVA, $p < 0.05$) in bacterial production ($0.44 \mu\text{g C l}^{-1} \text{h}^{-1}$) was observed after 3 hours of incubation. In cores incubated with sediment impacted by bauxite tailings, there was no difference in bacterial production with and without *C. notatus*. We conclude that *C. notatus* is an important bioturbator in Lake Batata, increasing the turnover rate of nitrogen (NH_4^+) at the sediment-water interface and bacterial production in cores incubated with natural sediment. It is also clear that bauxite tailings reduce the nutrients turnover rates in impacted regions of Lake Batata and influence bacterial production.

1. Introduction

The sediment of aquatic ecosystems is widely recognized as a reservoir of nutrients, organic compounds, and a large variety of solutes (WOODRUFF *et al.*, 1999). Most of these elements are unavailable to the majority of aquatic organisms, since many biogeochemical processes and much of the microbial activity that remobilises these elements take place generally in the first millimetres of the sediment (FENCHEL *et al.*, 1998, WANG *et al.*, 2001).

The flux of benthic nutrients through the sediment-water interface is a result of several microbial processes, such as ammonification, nitrification, denitrification, methanogenesis, oxidative phosphorylation and sulfate reduction, among others (CARMOUZE *et al.*, 1998). Along with these processes, several authors have emphasized the enhanced effects of the bioturbation process performed by benthic macroinvertebrates in the flux of these nutrients (RYSGAARD *et al.*, 1995; ROCHA, 1998; MULSOW and BOUDREAU, 1998). The resuspension of

solutes and particles, the ingestion, digestion and release of excreted products, as well as the changes in sediment characteristics caused by benthic macroinvertebrates have been noted as important stages in the processes of nutrient (nitrogen, phosphorus and carbon) remobilisation from the sediment to the water column in aquatic environments (FUKUHARA *et al.*, 1980; SVENSSON, 1998).

Nymphs of *Campsurus notatus* EATON 1868 (Ephemeroptera: Polimitarciidae), are the main species colonizing the area impacted by bauxite tailings in Lake Batata, where these nymphs dominate as regards density and biomass (FONSECA and ESTEVES, 1999). According to these authors, at the natural area of Lake Batata these nymphs are also observed, albeit in smaller numbers and frequency compared to the area impacted by bauxite tailings. At Lake Batata, as well as in Amazonian “várzea” (floodplain) lakes, where the sediment is densely colonized by individuals of this species, the significant ecological role of *C. notatus* nymphs as a food resource for several species of fishes, as well as their role in the process of decomposition of allochthonous plant material, has been noted (NOLTE, 1987).

The goal of this study was to investigate the influence of *C. notatus* nymphs and of the bauxite tailings on oxygen uptake, ammonium (NH_4^+) and dissolved organic carbon (DOC) flux, as well as on bacterioplankton production at the sediment-water interface.

2. Materials and Methods

2.1. Study Site

Lake Batata is a typical Brazilian Amazonian floodplain lake, located on the right bank of the Trombetas River ($1^\circ 30' \text{S}$ and $56^\circ 20' \text{W}$), under the direct influence of the Trombetas River. The hydrographic basin of the Trombetas River (including Lake Batata) is classified as clear water (SIOLI, 1984), with slightly acid waters (Table 1). Lake Batata has a total area ranging from 18 to 30 km^2 during the low water and high water periods respectively, with mean depths of 2.5 m (low water) and 10 m (high water) (PANOSSO *et al.*, 1995). In the high water period the bordering forest (igapó) is flooded, resulting in a large input of allochthonous material.

For ten years (1979–1989) around 50,000 $\text{m}^3 \text{d}^{-1}$ of bauxite tailings were dumped into Lake Batata, impacting 30% of the total area of the lake. The dumping of these tailings, rich in solid particles (clay) and iron and aluminum oxides, resulted in thick layers of this material settling over the natural sediment of Lake Batata. This impact resulted in changes in the physical, chemical and biological characteristics of the sediment (FONSECA *et al.*, 1998; ESTEVES and ENRICH-PRAST, 1998). The frequent resuspension of the bauxite tailings has increased the turbidity of the water column, resulting in a decrease in primary production as well as in changes in the planktonic communities in the impacted areas of Lake Batata (BOZELLI *et al.*, 2000).

Table 1. Limnological variables measured in the natural and impacted area of Batata lake, during June 1999.

		Depth (m)	Temperature ($^\circ\text{C}$)	Oxygen ($\text{mg} \cdot \text{l}^{-1}$)	Conductivity ($\mu\text{S} \cdot \text{cm}^{-1}$)	pH
Natural area	Surface	9.0	29.3	6.17	10.0	6.0
	Bottom		26.9	4.29	10.0	5.8
Impacted area	Surface	7.5	27.6	5.52	11.0	6.0
	Bottom		27.0	5.80	12.0	5.9

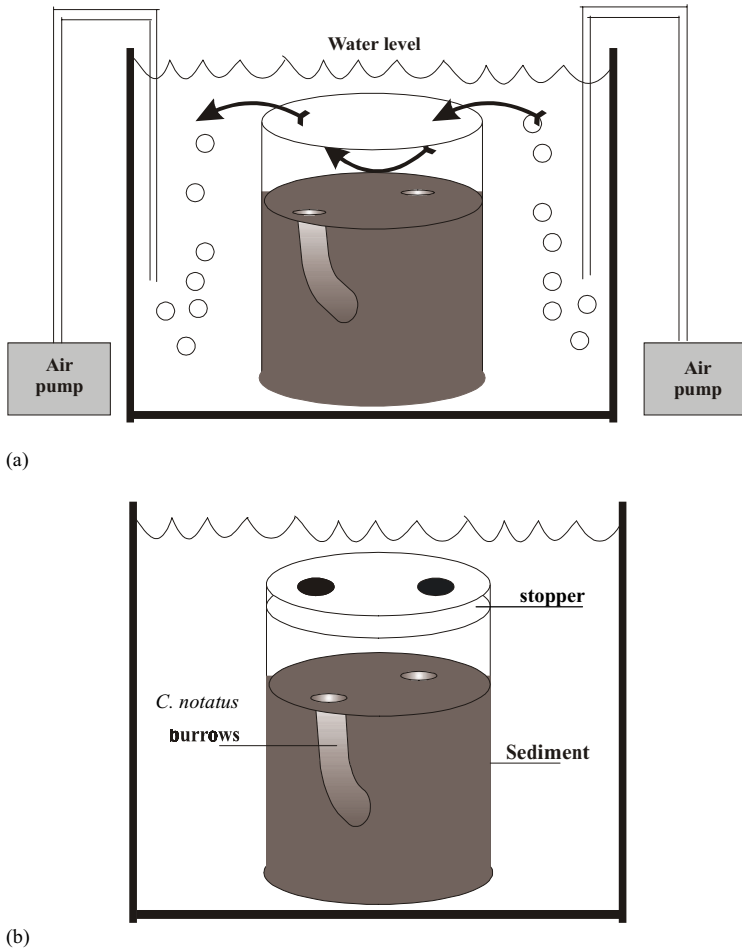


Figure 1. Scheme of the methodology used for cores incubation, (a) during the acclimatisation phase when the cores were kept under water without stoppers for stabilisation of temperature and dissolved oxygen concentrations, and (b) after the acclimatisation phase when the cores were stoppered, isolated and the incubation started.

2.2. Field Measurements

The depth, pH (pHmeter Analion), water temperature (thermometer FAC 400), dissolved oxygen (Winkler method, GOLTERMAN *et al.*, 1978) and electrical conductivity (conductivimeter Digimed CD-2P) were measured in the surface and in the bottom of the water column in each sampling station. The sediment was collected in each station with a corer sampler (AMBÜHL and BÜHRER, 1975) and from the first 5 cm we determined the total nitrogen concentration (MACKERETH *et al.*, 1978), total carbon concentration (TOC-5000 analyzer, Shimadzu), organic matter content by ignition at 550 °C during 4 h (JACKSON, 1962) and the interstitial water content by oven drying at 60 °C during 72 h (WETZEL and LIKENS, 1991).

2.3. Core Sampling and Incubation

The sediment-water interface was collected with a core sampler (AMBÜHL and BÜHRER, 1975). Samples were taken in June 1999 at two sites in Lake Batata: one located in the natural area and the other in the area impacted by bauxite tailings.

Sixteen undisturbed sediment plexiglas cores (4 cm internal diameter and 20 cm length) with 18 cm of sediment and 2 cm of water column were incubated with sediment from the natural and from the impacted area (8 cores each). Until the experimental time, the tubes were placed in styrofoam boxes (20 litres) with water from the two sampling sites. For 24 hours the tubes were kept submersed in the dark and unstoppered, allowing the exchange of water between the cores and the outside environment, aerated with an air pump (Fig. 1a). This procedure allowed the stabilization of temperature ($23.5 \text{ }^{\circ}\text{C} \pm 0.5$) and oxygen concentrations ($>95\%$ saturation) in the cores. The cores from natural and impacted areas were incubated in replicates with 0 (control), 1, 2 and 3 nymphs of *C. notatus* (densities of 0, 796, 1,592 and 2,388 ind. m^{-2} , respectively) and biomass ranging from 0 to 9.5 g DW m^{-2} . These densities are similar to observe in the Lake Batata and others Amazonian várzea lakes with density varied between 0 to 3,200 ind. m^{-2} (NOLTE, 1988; FONSECA and ESTEVES, 1999). After stabilization and acclimatization of the *C. notatus* nymphs, overlying water aliquots were taken from each core for determination of the initial concentrations of dissolved O_2 , NH_4^+ and DOC and the values of bacterial production. Finally, the cores were stoppered and isolated from the external medium for 3 hours (Fig. 1b), after which the final concentrations of dissolved oxygen, DOC and NH_4^+ and the bacterial production were measured.

2.4. Oxygen Uptake

The oxygen uptake was measured in each core, through the difference in initial concentration and that after the 3 hours incubation interval. The concentrations of dissolved O_2 were determined with a microelectrode (Unisense CO).

2.5. DOC and Ammonium (NH_4^+) Release

For determination of the concentrations of dissolved organic carbon (DOC) and ammonium (NH_4^+), water aliquots were sampled from each core at the beginning of the incubation and after 3 hours. The water aliquots were filtered with Whatman GF/C filters, stored in polyethylene flasks and frozen. The DOC concentrations were analyzed with a TOC carbon analyzer (TOC-5000, Shimadzu). The concentrations of NH_4^+ were determined by colorimetry (indophenol blue), as proposed by KOROLEFF (1978).

The determination of the rates of flux and uptake of the analyzed variables (ΔV) were estimated by the following formula:

$$\Delta V = [(f) - (i)] \cdot v / (0.00126 \text{ (m}^2) / t).$$

Where: $[f]$ – final concentration; $[i]$ – initial concentration; v – volume of overlying water in each core in litres; 0.00126 – area of each core in m^2 and t – incubation time in hours.

2.6. Bacterial Production

Bacterial production was determined in each core just before the tubes were stoppered (start), and after 2 and 3 hours of incubation. Bacterial production was evaluated from the incorporation of ^3H -leucine, according to SMITH and AZAM (1992). Three 1.3 ml aliquots of overlying water, from each core, were incubated in Eppendorff tubes containing 10 μl of ^3H -leucine (5-fold diluted solution, 159 Ci mmol^{-1} , Amersham), kept in the dark for one hour. A control was made for each sample, in which, in addition to the sample and the labeled leucine, 90 μl of 100% TCA (Trichloroacetic acid) was added. For conversion to $\mu\text{g C l}^{-1}$ the production of protein was multiplied by 0.86, as proposed by WETZEL and LIKENS (1991).

2.7. Data Treatments

The effect of *C. notatus* density on the NH_4^+ and COD flux, O_2 uptake and bacterial production was tested using multiple regression analyses and ordinary Two-Way ANOVA to compare simultaneous effect of density and sediments incubations (natural or impacted sediments). The sediments variables were compared by Mann-Whitney test. For all statistics tests, we use the GraphPad Prism, version 3.0 Software, Inc (MOTULSKY, 1999).

3. Results

3.1. Sediment Characteristics

The sediment from the natural area has a brownish color (silt), while the sediment in the impacted area has a reddish coloration due to the high concentrations of clay. For all variables (organic matter content, total nitrogen concentration, total carbon concentration and interstitial water content) the contents were significantly higher (Mann-Whitney, $p < 0.05$) in the natural sediment than in impacted (Table 2).

3.2. Oxygen Uptake

The cores incubated with sediment from the natural and impacted area showed a significant correlation between the O_2 uptake and the density of *C. notatus* nymphs ($r^2 = 0.82$, $p < 0.05$, polynomial regression, for natural sediments; $r^2 = 0.69$, $p < 0.05$, polynomial regression, for impacted sediments; Fig. 2). Furthermore, the density of *C. notatus* nymphs has a significant effect on oxygen uptake for both areas ($p < 0.05$, two-way ANOVA), but no significant difference was observed between the O_2 uptake for natural and impacted sediment cores incubations ($p \geq 0.05$, two-way ANOVA).

The rates of O_2 uptake in the cores with sediment from the natural area were $1.16 (\pm 0.27)$ $\text{mmol O}_2 \cdot \text{m}^{-2} \text{h}^{-1}$ (control) and $2.58 (\pm 0.20)$ $\text{mmol O}_2 \cdot \text{m}^{-2} \text{h}^{-1}$ (cores incubated with *C. notatus*). In the cores with sediment from the impacted area, the rates of O_2 uptake were $1.05 (\pm 0.04)$ $\text{mmol O}_2 \cdot \text{m}^{-2} \text{h}^{-1}$ (control) and $2.31 (\pm 0.51)$ $\text{mmol O}_2 \cdot \text{m}^{-2} \text{h}^{-1}$ (cores with *C. notatus*); i.e., O_2 uptake was twice higher in cores with nymphs than in controls, for both natural and impacted areas ($p < 0.05$, two-way ANOVA).

3.3. Ammonium Flux

The rates of ammonium release showed a significant correlation with the values of density of *C. notatus* nymphs in the cores incubated with sediment from the natural site

Table 2. Mean and standard deviation (SD) of variables measured on surface (0–5 cm) of the sediment from to natural and impacted sample sites, $n = 3$.

	Organic matter ($\text{mg} \cdot \text{g DW}^{-1}$)	Total Nitrogen ($\text{mg} \cdot \text{g DW}^{-1}$)	Total Carbon ($\text{mg} \cdot \text{g DW}^{-1}$)	Pore water (%)
Natural area	207.90 (1.90)	4.60 (0.82)	50.55 (2.45)	73.86 (4.68)
Impacted area	147.80 (2.40)	1.83 (0.12)	17.23 (2.22)	62.03 (1.68)

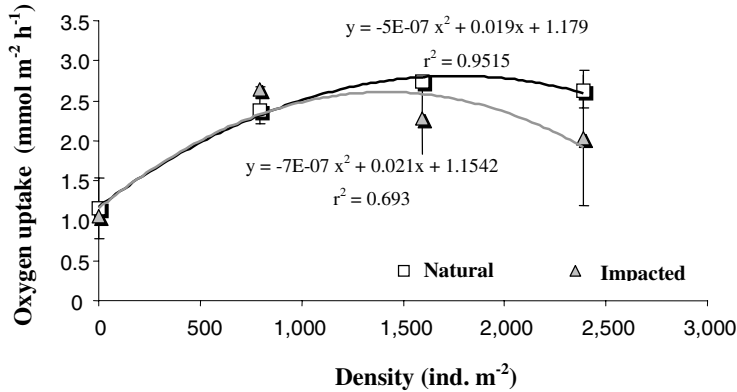


Figure 2. The relationship between oxygen uptake and density of *C. notatus* in cores with natural and impacted sediment (mean \pm S. D., $n = 4$).

($r^2 = 0.85$, $p < 0.05$, multiple non-linear regression; Fig. 3). On the other hand, no correlation was observed in the cores incubated with sediment from the impacted site ($r^2 = 0.47$, $p \geq 0.05$). The rates of NH_4^+ release were at least four-fold higher in the cores with natural sediment than in the cores with impacted sediment ($p < 0.001$, two-way ANOVA).

Higher rates of ammonium remobilization were observed in cores with *C. notatus* than in the controls in both sediments ($p < 0.05$, two-way ANOVA). In natural sediment controls, rates of ammonium release ranged from 24.7 to 32.6 $\mu\text{mol m}^{-2} \text{h}^{-1}$, while in the cores with *C. notatus* the rates ranged from 78.3 to 165.3 $\mu\text{mol m}^{-2} \text{h}^{-1}$. The cores incubated with the sediment impacted by bauxite tailings showed rates of ammonium release ranging from 3.8 to 6.0 $\mu\text{mol m}^{-2} \text{h}^{-1}$ in the cores without *C. notatus*, and 7.4 to 52.8 $\mu\text{mol m}^{-2} \text{h}^{-1}$ in the cores with *C. notatus*.

3.4. Dissolved Organic Carbon

Unlike the results for the rates of ammonium (NH_4^+) release, the results of the dissolved organic carbon (DOC) release showed no significant correlation ($p > 0.05$, r-Pearson) with

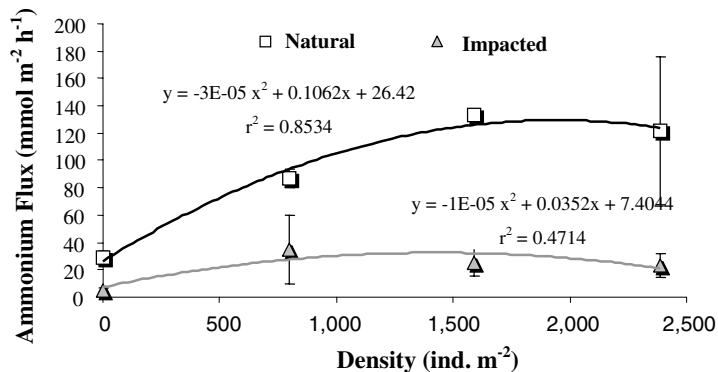


Figure 3. The ammonium release rate related to density of *C. notatus* in cores with natural and impacted sediment (mean \pm S. D., $n = 4$).

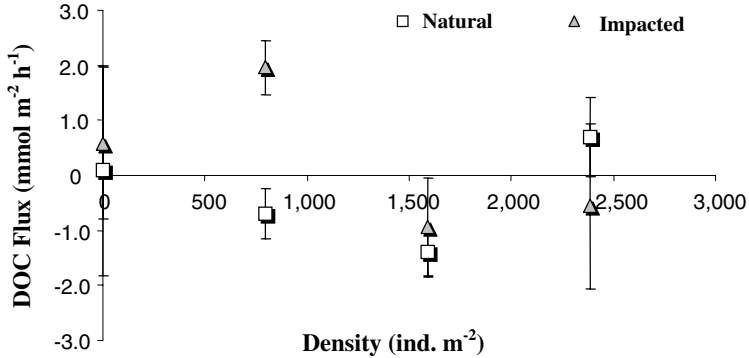


Figure 4. Dissolved organic carbon (DOC) release in some different density incubations of *C. notatus*, in the cores with natural and impacted sediment (mean \pm S. D., $n = 4$).

the nymphs density (Table 2, Fig. 4). No differences between the controls and the cores incubated with *C. notatus* were observed, neither between the cores with sediment from the two sampling sites ($p > 0.05$, two-way ANOVA).

3.5. Bacterial Production

Bacterial production before incubation was similar in the cores with *C. notatus* ($0.082 \pm 0.017 \mu\text{g C l}^{-1} \text{h}^{-1}$) and controls ($0.098 \pm 0.004 \mu\text{g C l}^{-1} \text{h}^{-1}$) in the cores incubated with natural sediment (Fig. 5a). After 2 and 3 hours of incubation, there was a significant increase ($p < 0.05$, two-way ANOVA) in bacterial production in the cores with *C. notatus* ($0.21 \pm 0.11 \mu\text{g C l}^{-1} \text{h}^{-1}$ and $0.44 \pm 0.18 \mu\text{g C l}^{-1} \text{h}^{-1}$, after 2 and 3 hours of incubation, respectively). No significant change in bacterial production was observed in the controls.

In the cores incubated with sediment from the impacted area (Fig. 5b), no significant differences in bacterial production were observed between cores with and without nymphs, throughout the entire incubation period. There was no correlation between the increase in the bacterial production and the density of the nymphs, in the cores with sediment from both areas ($p > 0.05$, two-way ANOVA). However, we observed an increase in bacterial production in the cores incubated with natural sediment and nymphs ($p < 0.01$, two-way ANOVA). In these cores, bacterial production was three-times higher than in the controls after 3 hours of incubation, as well as 3 times higher than in the cores with sediment from the impacted site.

4. Discussion and Conclusions

The efficiency of the bioturbation process may vary according to the body size of the benthic organisms and to their strategy for colonization of the sediment, which can be horizontal and/or vertical (SVENSSON, 1998). The nutrient flow from the sediment to the water column, induced by the bioturbation process, may be considered a major step in the supply of nutrients to the water column in some continental and marine aquatic environments (RABOUILLE *et al.*, 1998). In the present study, the *C. notatus* bioturbation was shown to be efficient in the remobilization of NH_4^+ from the sediment to the water column, with a strong correlation to the increase in oxygen uptake by the sediment. The body size of the nymphs of *C. notatus*, varying between 2 and 17 mm (FONSECA and ESTEVES, 2000), and the strategy

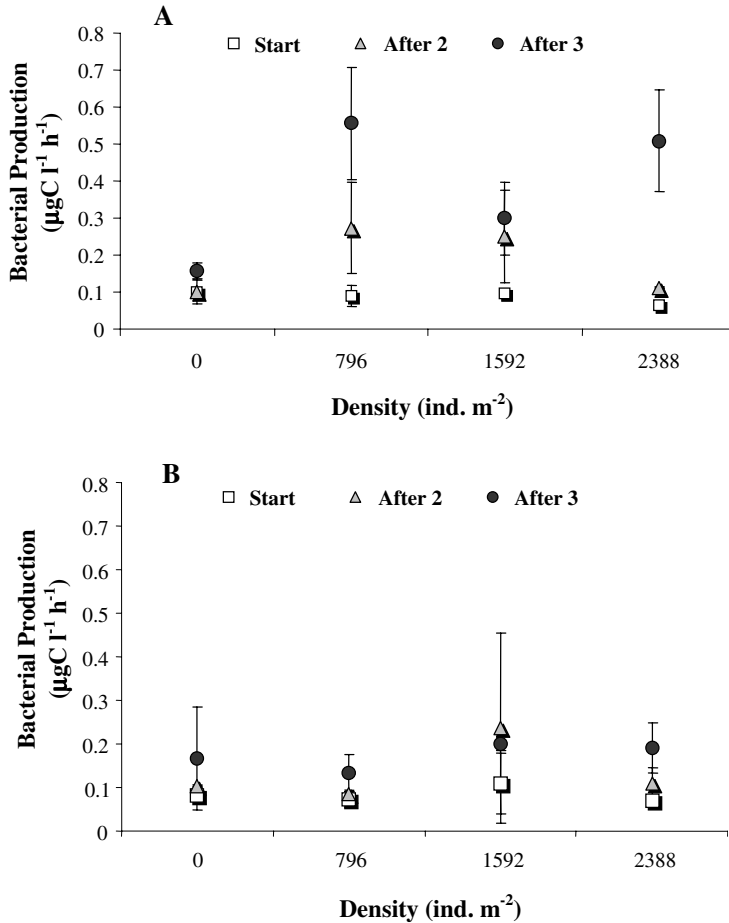


Figure 5. Bacterioplankton production ($\mu\text{g C l}^{-1} \text{h}^{-1}$) in the cores incubated with different *C. notatus* densities, in natural (a) and impacted (b) sediment-water interface, for different incubation times: Start (before incubation), after 2 hours and after 3 hours of incubation (mean \pm SD, $n = 4$).

of colonization of the sediment through large vertical burrows (more than 10 cm deep) where the nymphs create a continuous water flow, show their high capacity for bioturbation of the nymphs of *C. notatus* at Lake Batata. The same behavior was observed by NOLTE (1987) in nymphs of this species in other Amazonian várzea lakes, and by PEREIRA and DA SILVA (1991) in *C. melanocephalus* in fine-grained sediments of the São João River, northern coast of the state of Rio de Janeiro (southeastern Brazil).

The increase in oxygen uptake in the cores incubated with *C. notatus* over that in the controls, may be explained by the increased capacity of the nymphs for mixing the sediment, causing continuous water flow through the burrows and therefore expanding the oxidation layer of the sediment. This same phenomenon was observed by WANG *et al.* (2001) for two different species of insects (*Sialis valata* and *Hexagenia limbata*) in the Lake St. Joseph (Canada). According to SVENSSON (1998), the bioturbating activity stimulate the metabolic activity in the burrows, were the water-pumping increase the oxygen uptake by the bacteria respiration and contributes to the reoxidizing components. In previous study FONSECA *et al.*

(in press) showed that the biological oxygen demand of the nymphs is another factor in the increase of O₂ uptake, corresponding for 31% of the total O₂ uptake in the cores with natural sediment and 74% of the total O₂ uptake in the cores with bauxite tailings. This fact shows that the biochemical oxygen demand of the sediment in the natural area is an important factor in the increase in oxygen uptake because this element is used in other processes, not only by the nymphs respiration.

The increase in the oxygen uptake rates in sediments, subjected to bioturbation, was observed by several authors. As an example, ANDERSEN and JENSEN (1991) and SVENSSON and LEONARDSON (1996) postulated that O₂ uptake in bioturbated sediments is related to the respiration of the bioturbating organisms. On the other hand, according to SVENSSON (1997), a large part of the oxygen uptake is due to microbial processes stimulated by bioturbation.

The rates of ammonium release into the water column, induced by bioturbation, showed the importance of the *C. notatus* in the release of NH₄⁺ stored in the sediment. The results obtained in our research are similar to those observed by FUKUHARA and SAKAMOTO (1988), who found rates ranging from 29.8 to 268.7 μmol m⁻² h⁻¹ of release of the various forms of inorganic nitrogen from the sediment to the water column in Lake Suwa (a Japanese shallow eutrophic lake). According to these authors, higher remobilization rates are related to higher values of biomass of *Chironomus plumosus* and *Limnodrilus* spp. Similar results were also observed by SVENSSON (1997), at Lake Sövedsjön (a Sweden eutrophic lake), with rates of NH₄⁺ release between 31 μmol NH₄⁺ m⁻² h⁻¹ (without chironomids) and 124 μmol NH₄⁺ m⁻² h⁻¹ (with 200 ind m⁻² of *C. plumosus*). TÁTRAI (1986) studied the bioturbation process in Lake Balaton (Hungary) and observed higher rates of NH₄⁺ remobilization due to high density of larvae of *Chironomus* sp. in sandy and organic sediments, with values ranging from 505.9 μmol m⁻² h⁻¹ (for organic sediments) to 446.4 μmol m⁻² h⁻¹ (for sandy sediments), both with a maximum density of 5,000 ind. m⁻².

The results of our research showed that the rates of ammonium release in the natural sediment were four-fold higher than those observed in the sediment impacted by bauxite tailings. This fact can be attributed to the characteristics of the sediment related to the process of nutrient remobilization, since in the impacted area the settling of thick layers of bauxite tailings over the natural sediment resulted in the establishment of a sediment poorer in organic matter and in nutrients (Table 2), compared to the sediment from natural areas (FONSECA and ESTEVES, 1999).

The values of NH₄⁺ release calculated with the regression equation (Fig. 3) and the densities of *C. notatus* nymphs found in the natural area (40.0 ind. m⁻²) suggested that *C. notatus* increased by 0.74 mmol NH₄⁺ m⁻² d⁻¹ the NH₄⁺ release in the natural area. According to ROLAND and ESTEVES (1993) and FERRÃO-FILHO and ESTEVES (1994), the higher rate of nitrogen sedimentation is 12.3 mmol N m⁻² d⁻¹ at the natural area of Lake Batata. We may observe that the high ammonium remobilization rates stimulated by bioturbation activity of the *C. notatus* nymphs (40.0 ind.m⁻²) in natural area represent 6.0% of the total nitrogen that settled in the natural area. These results indicate a high turnover rate of the sedimentary nitrogen fractions, through NH₄⁺ remobilization by the bioturbation of the *C. notatus* nymphs.

According to ROLAND and ESTEVES (1993), the sedimentation rate increases in Lake Batata during the high water period, but this rate is not proportional to the increase in phosphorus, nitrogen and carbon concentrations in the sediment. This is related to the marked resuspension process, under the direct influence of periodical winds that mix the water column (ROLAND and ESTEVES, 1993). In the present investigation we have shown that, in addition to winds, the process of bioturbation by *C. notatus* nymphs is an important step in the remobilization of dissolved nutrients deposited on the bottom of Lake Batata. This process can be considered as the main step in the process of ammonium remobilization from the sediment, since the rates of nitrification and denitrification in the sediment of the impacted and natural areas in Lake Batata are negligible (ESTEVES and ENRICH-PRAST, 1998).

The effect of the bioturbation process on nutrients released to the sediment-water interface has been noted as a major link in the metabolism of continental aquatic ecosystems (BERNASCONI *et al.*, 1997; HEYER and CALFF, 1998), as well as responsible for the increase in the rates of production of phytoplanktonic communities or as a source of nutrients in the maintenance of primary production (POMOROY *et al.*, 1983). HOPKINSON *et al.* (1998), studying the effect of the nutrient flux across the sediment-water interface on bacterial growth in Parker River and Plum Island Sound estuary in northern Massachusetts, USA, suggested that there were gross fluxes of organic matter across the sediment-water interface that were not apparent from net changes in DOC concentration in the overlying water pool. There was also an indication that planktonic bacteria were supplementing their diet of organic matter, which is deficient in nitrogen as indicated by C/N ratios up to 60:1, with inorganic N remineralized in the sediments and exchanged with the overlying water. HOPKINSON *et al.* (1998) stated that benthic systems must be viewed not only as important sites of inorganic nutrient remineralization in support of planktonic primary producers, but also as important sites of dissolved organic matter generation in support of bacterioplankton production.

An increase in bacterial production in the cores with natural sediment and *C. notatus* nymphs was observed in comparison with the cores without nymphs. On the other hand, in the cores incubated with sediment and bauxite tailings, no change in the bacterial production was observed between the cores with and without nymphs. These results indicate that the effect of the bioturbation and the release of NH_4^+ , probably were reflected in an increase in bacterial activity in the cores incubated with the natural sediment. The bacterial production values found in our investigation are within the range of those measured in the water column of Lake Batata by ANESIO *et al.* (1997) and THOMAZ *et al.* (1998), who found values for bacterial production between 0.18 and 1.38 $\mu\text{g C l}^{-1} \text{h}^{-1}$ (both studies took place in the high water period). However, the results of ANÉSIO *et al.* (1997) showed greater values for bacterial production in the impacted area of Lake Batata, unlike the values found in our investigation, where higher values for production were measured in the natural area. BENNER *et al.* (1995), studying black and white water Amazonian environments, measured values for bacterial production between 0.44 and 1.83 $\mu\text{g C l}^{-1} \text{h}^{-1}$. The results found by the different authors show similar values to those found in our research.

THOMAZ *et al.* (1998) showed a strong correlation between DOC concentrations and bacterial abundance and production, in different clear water bodies in the central Amazon region. BENNER *et al.* (1995) showed that the concentrations of carbon, nitrogen and phosphorus are limiting factors for bacterial production in Amazonian white and black water environments. These results suggest a possible stimulation of nutrient release rates at the sediment-water interface, by the process of bioturbation, over the increase in the bacterial production observed in the cores with sediment from the natural areas of Lake Batata.

The results found in our research showed the bioturbating capacity of the *C. notatus* nymphs, and the importance of this process, contributing for the increase in the ammonium remobilization rates between the sediment and the water column of Lake Batata, and therefore the increase in the availability of this element for planktonic organisms. The settling of thick layers of bauxite tailings over the natural sediment of Lake Batata resulted in the establishment of an extremely nutrient-poor, fine grained sediment dominated by clays ($<2.0 \mu\text{m}$) in the impacted areas, altering the biological characteristics of this sediment. This new sediment formed in the impacted area of Lake Batata acts as a physical barrier between the natural sediment (nutrient-rich) and the water column. The reduction of ammonium flux at the sediment-water interface and the low values of bacterial production show the negative effect of the settling of the bauxite tailings on nutrient cycling in the benthos of Lake Batata. In the cores with natural sediment, the effect of the process of bioturbation by *C. notatus* nymphs was quite strong, inducing an increase in bacterial production and showing an interaction between the benthic cycles and the interface with the water column.

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