MERCURY IN FISH OF THE TAPAJÓS RIVER IN THE BRAZILIAN AMAZON

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ABSTRACT

We studied total mercury (Hg) concentrations, as well as bioaccumulation and bioamplification of Hg in the ichtyofauna of three lakes located on the Tapajós River. Particular attention was paid to possible temporal and spatial variations in Hg levels. The results of two sampling campaigns corresponding to the rainy season (April-May/2000) and rising water season (January/2001) are presented. Bioamplification of Hg through the trophic chains of the three lakes was observed. During the rainy season, Hg concentrations in 31% of predator fish were above the critical value of 500 ng/g, compared to only 28% in the rising water period. Linear or curvilinear positive correlations between Hg concentrations of muscular tissue and the total length of fish were rarely observed. Various species of commercial importance did not show any variation in Hg concentrations with increasing length of fish. Linear-negative and non-linear positive or negative correlations with Hg throughout the development of fish were also observed. Our data suggest that Hg concentrations may vary seasonally. On the other hand, no spatial variation in Hg concentrations was observed for most of the studied species over the two seasons. These findings suggest that it is important to consider the different patterns of Hg accumulation as well as the spatial-temporal variations of Hg levels in fish, when implementing measures to inform the populations at risk of Hg exposure.

Key-words: Amazon; fish; mercury.

INTRODUCTION

The presence of mercury (Hg) in various compartments of aquatic ecosystems is an increasingly worrying problem in the Amazon basin. The first studies relating to this problem date from more or less twenty years ago. The two main sources recognized as being responsible for this contamination are gold prospecting (MARTINELLI et al., 1988; MALM et al., 1990; LACERDA and SALOMONS, 1991; PFEIFFER et al., 1991; PFEIFFER et al., 1993) and slash and burn agriculture (ROULET et al., 1998a; 1998b, FARELLA et al., 2001, FARELLA, 2005). Various pieces of research carried out on populations that live along river banks in the Amazon revealed that fish is an important element in the diet of these people. The enquiries we made close to the area of this study showed that 100% of those questioned eat fish (LEBEL et al., 1997; DOLBEC et al., 2001; PASSOS et al., 2001; PASSOS, 2002). This latter author, when studying the annual diet of the population of Brasília Legal, identified average consumption of eight fish meals per week. Furthermore, Lebel et al. (1997) observed that exposure to Hg of people living on the banks of the Tapajós River is directly related to fish consumption. Other research has clearly identified alterations in the cytogenetic properties of the lymphocytes and of the nervous system associated with chronic exposure to mercury (LEBEL et al., 1997; 1998; AMORIM et al., 2000).

It is well known that once Hg has been released into the environment it can accumulate in muscle tissue and concentrations increase as a function of the weight gain and age increase of aquatic organisms (PHILLIPS et al., 1980; LANGE et al., 1993; DRISCOLL et al., 1994; STAFFORD and HAINES, 1997). This is the phenomenon of the bioaccumulation of this metal, which is explained principally by its great affinity for fat and proteins and also by the low rate at which this element is eliminated (MEILI, 1991). It is also recognized that concentrations of Hg in organisms increase as they move along the trophic chains (CABANA and RASMUSSEN, 1994). In the Amazon region the biomagnification process of Hg has already been identified several times (BARBOSA et al., 1995; MALM et al., 1995; SAMPAIO DA SILVA, 2002; SAMPAIO DA SILVA et al., 2005), although research on its bioaccumulation has been rarely carried out. In a study they did with various species of fish from the Tapajós River, Roulet and Maury-Branchet (2001) for the first time observed five types of Hg bioaccumulation over the life cycle of these organisms. In most of the research on contamination of Amazon fish by Hg neither the bio-ecological aspects of the species, nor the influence of the ecology of the ecosystems as a function of the hydrological cycle were considered. At present all and any influence of this nature is unknown, making any comparative interpretation of the state of contamination of the fish sampled from different ecosystems even more difficult.

This research is part of one of the themes of the second phase of the Caruso Project, financed by the International Development Research Center (CRDI-Canada). Our aim was to identify the average concentrations of Hg in the fish sample we took from three lakes on the lower Tapajós River and to study the bioaccumulation and biomagnification process of this metal in ichthyofauna. Special attention was paid to the various spatial-temporal variations in the concentrations of Hg, with the aim of observing the influence of these factors on the accumulation of Hg in Amazonian fish.

METHODOLOGY

We did this study in three lakes: Bom Intento (3°58'41''S, 55°35'22''W), Cupu (4°02'07''S, 55°35'63''W) and Pereira (4°02'06''S, 55°35'64''W) (Figure 1). These three lakes are located on the lower Tapajós River and are subject to various anthropic impacts, such as the removal of riverbank vegetation and the traditional slash and burn agriculture. The main difference between the lakes is the number of inhabitants (Population of Cupu > Population of Pereira > Population of Bom Intento).

In the lower Amazon, due to variations in the hydrological cycle, it is common to identify two fairly clearly defined periods that have very different characteristics over the period of a year. These are the times when the river is in full flood [rainy season] and when it is 'dry' [low]. According to the local population these two periods are equivalent to the Amazon winter and summer, respectively. Furthermore, there are also two intermediary periods that correspond to the waters in the river rising and falling. For this research we caught fish on two occasions. The first during the rainy season (April-May/ 2000) and the second during the time the water in the river was rising (January/2001).

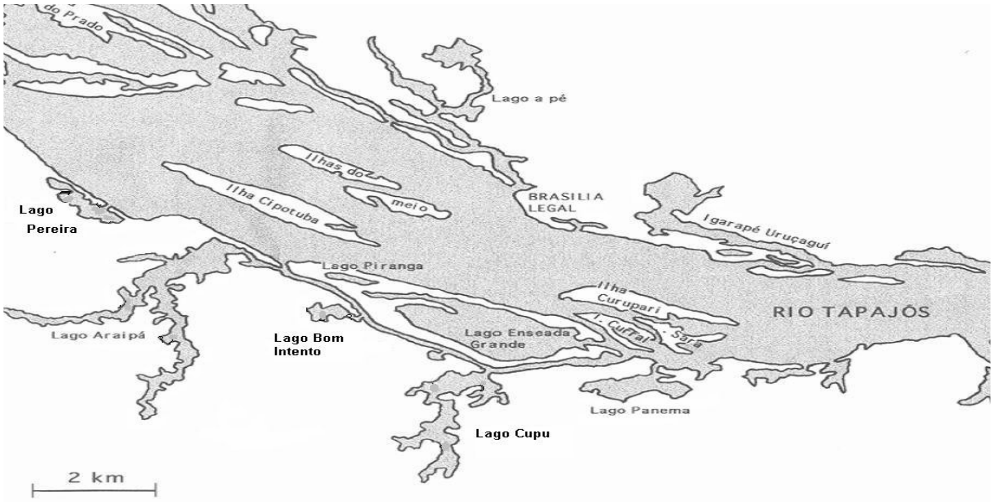


Figure 1 – Schematic diagram of the study area

The three lakes had similar physical and chemical characteristics (pH, conductivity, temperature, transparency and dissolved oxygen) during the two periods of our study (Peleja, 2002). The factor that varied most between the two moments was in reality the depth (a difference of 2.5 meters). The fish sample was carried out using fishing nets of varying mesh size in order to catch different sized specimens. The species we caught were identified according to Ferreira et al. (1998). They were the following: *Hypostosmus emarginatus*, *Schizodon fasciatus, S. vittatum, Leporinus friderici*, *L. fasciatus*, *L. affinis*, *Cichlasoma amazonarum*, *Curimata inornata*, *Rhytiodon argenteofuscus*, *Potamorhina altamazonica*, *Geophagus proximus*, *Hemiodus unimaculatus*, *Semaprochilodus insignis*, *Raphiodon vulpinus*, *Plagioscion squamosissimus*, *Serrasalmus eigenmanni*, *S. rhombeus, Pygocentrus nattereri*, *Pseudoplatystoma fasciatus*, *Hoplias malabaricus*, *Cichla monoculus*, *Cichla temensis*, *Cichla sp*, *Mylossoma aureum*, *Mylossoma sp*, *Ageneiosus brevifilis*, *Ageneiosus sp*, *Platydoras costatus*, *Osteoglossum bicirhosum*, *Triportheus albus*, *Satonoperca acuticeps*, *Pellona castelnaeana*, *Liposarcus pardalis*, *Crenicichla ornata*, *Metynnis argenteus*, *Catoprion mento*, *Hypophthalmus marginatus* and *Symphysodon aequifasciatus*.

These species are frequently eaten by the local population and are well distributed throughout the whole of the Amazon basin. The procedure we used for handling the fish was as follows: identify the species, record the morphometric measurements (weight and length), take a sample of the muscle tissue, without skin or bones and finally freeze the sample until we were able to analyse it in the laboratory. We caught 777 fish, representing 38 species, more precisely 356 specimens during the rainy season and 421 when the river was rising. Analyses of the samples coming from the first experimental fishing expedition were carried out in the laboratory of the University of Quebec in Montreal using the atomic fluorescence method, as described by Pichet et al. (1999). The analytic procedure we used for determining total Hg in the fish we caught during the second expedition was atomic absorption, in line with the methodology described by Akagi et al. (1995); this was done in the Cohema laboratory at the Evandro Chagas Institute in Belém. An exercise in intercalibration between the laboratories was carried out so that there was a compatibility between the concentrations obtained in the two of them. In this exercise 47 fish samples were analysed in both laboratories and a correlation factor (r^2) of 95% was obtained ($p < 0.0001$). With the aim of expressing the values according to a common method the following correction factor UQAM = (Cohema – 4.243)/1.25), obtained from the regression of this exercise, was applied to the concentrations we obtained in the Cohema laboratory.

Taking into consideration the variety of species we caught according to the hydrological cycle and/or the location of the ecosystems we studied, the definition of key species was necessary for the study of the temporal and spatial variations of Hg concentrations. In the first analysis the criterion established for selecting the key species was their presence in the same lake at both moments we studied, while for analysis of the spatial variation the criterion was their presence in all three lakes (or sometimes only in two) in both collection periods. For statistical validation of the temporal variation of Hg concentrations in the fish samples from the three lakes Student and Mann-Whitney tests were applied. For the majority of the species we studied the application conditions of a parametric test were not respected, so that the **p** values presented in Table 7 result in a non-parametric analysis. The parametric method was applied only to three species (*H. unimaculatus* – Lake Bom Intento; *S. fasciatus* and *P. squamosissimus* – Lake Pereira). The concentrations were judged to be statistically different from one collection period to another, when $p<0.05$. To test the spatial variation of Hg concentrations in the species that were present in the three ecosystems, the Kruskall-Wallis test was applied. In cases in which heterogeneity was seen to be present the application of the non-parametric Mann-Whitney test was necessary to identify the group that was statistically different from the others.

RESULTS

Concentrations of Hg in the fish

Only the fish-eating species exceeded 500 ng/g (wet weight) of Hg, which is the safe limit specified by the WHO (Brazil, 1998; WHO, 1994). Exactly 12% of all species caught had concentrations of Hg greater than this value during the two collection periods. During the rainy season, 31% of fish-eating fish (n=137) had concentrations over 500 n/g, as opposed to 28% of the fish-eaters (n=184) when the river was rising. Hg concentrations in the fish from the three lakes are very variable. In Lake Bom Intento, they vary from 23 to 551 ng/g (wet weight) during the rainy season and from 13 to 1177 ng/g when river waters are rising (Tables 1 and 2). In Lake Cupu, the variation went from 22 to 819 ng/g and from 39 to 1576 ng/g in the two respective periods analysed (Tables 3 and 4). In Lake Pereira, the variation went from 11 to 1067 ng/g and from 18 to 1267 ng/g during the rainy season and with river waters rising, respectively (Tables 5 and 6). Average concentrations of Hg per species and per sample period of all fish caught in the three lakes are shown in Tables 1 to 6.

Table 1 – Average Hg concentrations of all fish caught in Lake Bom Intento during the rainy season, 2000

Species	(n)	Diet [a]	Hg (ng/g wet weight)	Length (cm)
Curimata inornata	03	NP	66±19	15±1.3
Geophagus proximus	05	NP	57±21	16.5±3.3
Schizodon fasciatus	02	NP	28±7	28.3±1.1
Hemiodus unimaculatus	25	NP	58±37	21.2±1.0
Catoprion mento	01	NP	87	17.3
Serrasalmus eigenmanni	02	P	140±21	15.5±0.7
Pygocentrus nattereri	04	P	366±130	20.1±3.3
Hoplias malabaricus	04	P	152±81	22.8±10.0
Cichla temensis	02	P	129±101	28.8±2.5
Cichla monoculus	02	P	163±15	22.2±3.3

[a] NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).

Table 2 – Average Hg concentrations of all fish caught in Lake Bom Intento when the river was rising, 2001

Species	**(n)**	**Diet** [a]	**Hg (ng/g wet weight)**	**Length (cm)**
Potamorhina altamazonica	05	NP	31±8	17.2±1.0
Curimata inornata	35	NP	32±14	15.9±2.4
Semaprochilodus insignis	02	NP	24±6	21.2±0.0
Hoplosternum litoralles	01	NP	144	20.0
Liposarcus pardalis	07	NP	69±28	28.8±6.2
Cichlasoma amazonarum	01	NP	15	24.0
Satanoperca acuticeps	05	NP	150±97	21.5±2.6
Symphysodon aequifasciatus	02	NP	177±84	14.4±0.8
Astronotus crassipinnis	01	NP	90	22.0
Schizodon vittatum	15	NP	48±20	27.1±2.1
Schizodon fasciatus	06	NP	71±54	23.0±4.5
Geophagus proximus	07	NP	50±29	18.9±4.3
Hemiodus unimaculatus	12	NP	49±28	20.3±5.0
Platydoras costatus	01	NP	75	19.0
Osteoglossum bicirrhosum	03	P	537±323	46.4±3.9
Hoplias malabaricus	08	P	416±168	28.6±3.5
Pygocentrus nattereri	08	P	405±178	19.0±2.5
Serrasalmus rhombeus	03	P	383±483	18.0±5.8
Serrasalmus eigenmanni	04	P	272±248	15.2±1.0
Cichla monoculus	05	P	456±188	27.2±5.3
Cichla sp	04	P	236±46	24.1±2.6
Raphiodon vulpinus	02	P	488±140	20.5±5.0
Pseudoplatystoma tigrinus	01	P	376	45.5
Plagioscion squamosissimus	07	P	331±161	25.5±2.9

[a] *NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).*

Table 3 – Average Hg concentrations of all fish caught in Lake Cupu during the rainy season, 2000

Species	(n)	Diet [a]	Hg (ng/g wet weight)	Length (cm)
Curimata inornata	02	NP	53±13	14.3±0.4
Geophagus proximus	04	NP	67±37	21.6±2.5
Schizodon fasciatus	12	NP	71±65	26.7±3.8
Schizodon vittatum	05	NP	125±92	25.1±4.8
Leporinus friderici	02	NP	52±22	26.8±1.8
Leporinus fasciatus	04	NP	148±88.4	26.1±4.9
Hemiodus unimaculatus	17	NP	85±43	20.1±2.3
Serrasalmus eigenmanni	02	P	342±129	19.1±0.7
Pygocentrus nattereri	02	P	74±23	17.0±1.3
Hoplias malabaricus	01	P	253	25.0
Cichla temensis	11	P	449±155	39.1±9.8
Cichla monoculus	04	P	631±46	33.7±5.0
Osteoglossum bicirrhosum	01	P	819	49.0
Pellona castelnaeana	05	P	450±84.5	31.3±6.2
Cangóia (espécie não-identificada)	03	P	435±129	31.9±3.0

[a] *NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).*

Table 4 – Average Hg concentrations of all fish caught in Lake Cupu when the river was rising, 2001

Species	(n)	Diet [a]	Hg (ng/g wet weight)	Length (cm)
Potamorhina altamazonica	01	NP	28	14.6
Liposarcus pardalis	02	NP	79±14.1	35.8±3.9
Schizodon fasciatus	08	NP	163±78	19.2±3.1
Schizodon vittatum	02	NP	236±153	21.9±0.7
Leporinus affinis	03	NP	117±39	24.1±1.9
Hypophthalmus marginatus	02	NP	171±122	35.5±0.1
Hemiodus unimaculatus	20	NP	52±21.8	15.8±3.8
Metynnis argenteus	02	NP	67±2.1	13.9±0.1
Serrasalmus eigenmanni	14	P	202±150	18.0±3.5
Pygocentrus nattereri	01	P	524	21.2
Serrasalmus rhombeus	14	P	122±54	13.9±3.2
Cichla monoculus	03	P	426±49	37.4±11.0
Cichla temensis	08	P	490±164	35.1±11.1
Cichla sp	02	P	409±11.3	40.5±4.3
Acestrorhynchus falcirostris	02	P	758±8.5	16.2±2.1
Osteoglossum bicirrhosum	01	P	1257	52.4
Pellona castelnaeana	03	P	633±268	39.7±4.6
Pseudoplatystoma tigrinus	01	P	560	49.0
Plagioscion squamosissimus	06	P	387±152	29.3±6.0

[a] *NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).*

Table 5 – Average Hg concentrations of all fish caught in Lake Pereira during the rainy season, 2000

Species	(n)	Diet [a]	Hg (ng/g wet weight)	Length (cm)
Semaprochilodus insignis	04	NP	50±31	25.7±3.7
Schizodon fasciatus	54	NP	54±44.5	27.7±2.2
Leporinus fasciatus	07	NP	130±113.6	27.3±3.0
Leporinus friderici	08	NP	44±14	25.0±2.2
Geophagus proximus	10	NP	70±38	16.6±6.1
Mylossoma aureum	13	NP	36±15.5	13.9±1.0
Mylossoma sp	15	NP	46±34	14.3±1.0
Hemiodus unimaculatus	26	NP	55±34	21.1±3.3
Triportheus albus	02	NP	218±43	15.9±0.7
Crenicichla sp	03	P	225±79.1	24.4±7.4
Serrasalmus eigenmanni	16	P	471±117	17.0±0.8
Pygocentrus nattereri	10	P	317±301	19.3±3.8
Serrasalmus rhombeus	11	P	136±249	16.3±7.3
Hoplias malabaricus	04	P	383±116	34.4±5.4
Cichla monoculus	06	P	420±189	31.7±8.7
Cichla temensis	08	P	346±233	28.9±8.4
Raphiodon vulpinus	09	P	496±238	32.7±5.7
Pellona castelnaeana	11	P	516±267	36.0±2.3
Plagioscion squamosissimus	12	P	463±245	30.5±2.9
Cangóia (espécie não-identificada)	04	P	406±170	30.7±7.3

[a] NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).

Table 6 – Average Hg concentrations of all fish caught in Lake Pereira when the river was rising, 2001

Species	(n)	Diet [a]	Hg (ng/g wet weight)	Length (cm)
Potamorhina altamazonica	08	NP	28±16	13.7±2.3
Curimata inornata	26	NP	32±12	16.6±2.4
Schizodon fasciatus	04	NP	92±93	27.1±2.8
Schizodon vittatum	07	NP	35±23	27.8±3.2
Rhytiodus argenteofuscus	12	NP	131±46	18.2±3.9
Leporinus friderici	04	NP	131±26	17
Leporinus affinis	01	NP	80	25.5
Anostomoides laticeps	01	NP	447	15.5
Geophagus proximus	05	NP	33±19	17.1±4.0
Satanoperca acuticeps	03	NP	38±15	19.7±4.7
Hemiodus unimaculatus	11	NP	35±28.9	17.5±2.1
Triportheus albus	10	NP	153±34	8.4±0.8
Ageneiosus brevifilis	06	P	615±251	14.9±2.3
Ageneiosus sp	02	P	438±175	18.7±0.2
Oxydoras niger	01	NP	167	43.7
Platydoras costatus	08	NP	180±57	14.7±3.6
Serrasalmus eigenmanni	04	P	428±340	15.8±2.5
Pygocentrus nattereri	05	P	419±211	18.4±4.0
Serrasalmus rhombeus	01	P	881	22.5
Hoplias malabaricus	02	P	351±189	30.1±2.0
Cichla monoculus	01	P	381	30.0
Cichla temensis	01	P	115	22.5
Pseudoplatystoma tigrinus	03	P	371±166	46.6±7.0
Raphiodon vulpinus	04	P	598±399	32.2±6.1
Plagioscion squamosissimus	51	P	373±152	28.3±4.9

[a] NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).

The biomagnification of Hg in the fish from the three lakes studied

The effect of the biomagnification of Hg among the non-predatory and predatory fish caught in the different ecosystems we studied can be clearly seen during the two sample periods. Predatory fish (P) have on average five times more Hg than non-predatory fish (NP).

Average concentrations of Hg in the NP from Lakes Bom Intento, Cupu and Pereira in 2000 were respectively: 59±33.4 ng/g (19.9±2.8 cm); 82±48.6 ng/g (22.3±4.5 cm) and 60±83.2 ng/g (22.4±6.2 cm), while average Hg concentrations in the P were respectively: 210±130.1 ng/g (21.8±6.4 cm); 455±195.1 ng/g (33.9±10.4 cm) and 400±228.8 ng/g (25.1±8.7 cm). In 2001 average Hg concentrations in the NP from the three above mentioned lakes were respectively: 80±65.0 ng/g (21.5±5.4 cm); 114±90.9 ng/g (16.5±3.8 cm) and 106±93.6 ng/g (15.8±5.1 cm), while average concentrations of Hg in the P were respectively: 478±250.3 ng/g (24.9±8.7 cm); 443±344.2 ng/g (26.9±13.9 cm) and 521±243.8 ng/g (26.6±7.8 cm). The data in brackets represent the average total length of each group.

Temporal influence on concentrations of Hg in some species

In this research levels of Hg are always correlated with the length of the fish and not with their weight, because length is not influenced by variations such as the availability of food and the temporal physiological phenomena of each species. Furthermore, in our study of temporal and spatial variations only adult specimens were considered because they already have a stable diet.

Hemiodus unimaculatus, an omnivorous species that was very common in the three lakes during both periods we studied, showed no temporal variation in Lake Bom Intento. However, during the rainy season we observed higher average concentrations in specimens caught in Lake Cupu (p=0.0047) and in Lake Pereira (p=0.0388), in comparison with when waters were rising. In *Schizodon fasciatus* from Lake Pereira, concentrations of Hg are statistically higher during the rainy season, while in Lake Cupu we identified no significant variation. We observed the same situation in *C. monoculus* from Lake Cupu when compared with specimens caught in Lake Bom Intento (Table 7).

Table 7 – Average Hg concentrations and average length of key species used in the study of temporal variations of this contaminant. The number of samples is shown in brackets for each of the periods studied ($p < 0.05$; ** $p < 0.01$)*

LAKE **Species**	**<u>Rainy season</u>** **Hg (ng/g wet weight)**	**<u>River rising</u>** **Hg (ng/g wet weight)**	**p**	**Length (cm)** *Rainy season*	**Length (cm)** *River rising*
BOM INTENTO					
G. proximus (NP) [a]	57±21 (5)	47±31 (6)		16.5±3.3	17.6±2.9
S. fasciatus (NP)	28±7 (2)	71±38 (2)		28.3±1.1	28.7±0.6
H. unimaculatus (NP)	58±37 (25)	40±20 (9)		21.2±1.0	21.2±1.6
H. malabaricus (P)	212±69 (2)	435±194 (6)		31.3±3.2	30.0±2.4
P. nattereri (P)	366±130 (4)	404±178 (8)		20.1±2.3	20.0±2.2
S. eigenmanni (P)	140±21 (2)	272±248 (4)		15.5±0.7	15.1±0.9
C. monoculus (P)	163± 15 (2)	319±19 (3)		22.2±3.3	23.9±2.4
CUPU					
S. vittatum (NP)	116±83 (5)	196±81 (5)		23.0±3.0	21.4±0.8
S. fasciatus (NP)	142±124 (3)	236±153 (2)		21.8±1.5	21.9±0.7
H. unimaculatus (NP)	87±43 (16)	43±13 (10)	**	19.7±1.5	18.5±3.0
C. temensis (P)	449±155 (11)	527±134 (7)		39.1±9.8	35.5±9.7
C. monoculus (P)	631±46 (4)	426±49 (3)	*	33.7±5.0	37.4±11.0
P. castelnaeana (P)	466±89 (4)	663±268 (3)		35.5±2.3	39.7±4.6
PEREIRA					
G. proximus (NP)	72±39 (9)	33±19 (5)		15.4±5.2	17.1±4.0
S. fasciatus (NP)	54±44 (54)	92±93 (4)		27.2±2.2	27.1±2.8
S. vittatum (NP)	143±119 (6)	35±23 (7)	*	27.0±3.2	27.8±3.2
H. unimaculatus (NP)	44±24 (21)	33±31 (9)	*	19.6±1.3	19.0±1.0
P. nattereri (P)	317±301 (10)	419±211 (5)		19.3±3.8	18.4±4.0
R. vulpinus (P)	527±235 (8)	598±399 (4)		30.9±1.5	32.2±6.1
H. malabaricus (P)	383±116 (4)	351±189 (2)		31.4±5.4	30.1±2.0
P. squamosissimus (P)	463±215 (12)	410±128 (41)		30.5±2.9	28.7±3.3

[a] *NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).*

Spatial influence on concentrations of Hg in fish

The fish species used in the study of the influence of spatial variations on the levels of Hg in the fish during the two periods analyzed are shown in Tables 8 and 9. The specimens we considered are of similar size and there is no significant statistical difference between their lengths.

During the rainy season we considered eight species in our study of the spatial influence on Hg levels in the muscle tissue of fish. *Hemiodus unimaculatus* and *Hoplias malabaricus* were the only species to show a significant inter-lake variation of Hg levels during the rainy season (Kruskall-Wallis p test = 0.00521 and Mann-Whitney p test = 0.0339 respectively). For the first species higher concentrations of Hg were identified in individuals caught in Lake Cupu, while for *H. malabaricus*, higher average levels of Hg were observed in examples caught in Lake Pereira (Table 8). No significant spatial variation in the levels of Hg was observed in the majority of species when the river was rising, except in *Schizodon vittatum* (p=0.0307) (Table 9). Therefore considering the absence of any inter-lake variation of Hg levels in the majority of species we studied, fish coming from the three environments were regrouped to characterize the bioaccumulation of this metal during the development of each species.

Table 8 – Spatial variation of average Hg concentrations of key species caught during the rainy season on the Tapajós River, 2000. The number of samples is shown in brackets (p < 0.05; ** p < 0.01 – Mann-Whitney test)*

Species caught in the 3 lakes	Hg (ng/g wet weight)	Length (cm)	Lakes compared	p
Geophagus proximus (NP)[a]				
Lake Bom Intento (4)	50±13	17.2±3.4	Bom Intento vs. Cupu	
Lake Cupu (3)	50±17	20.8±2.4	Bom Intento vs. Pereira	
Lake Pereira (8)	56±28	18.7±4.8	Cupu vs. Pereira	
Schizodon fasciatus (NP)				
Lake Bom Intento (2)	28±7	28.3±1.1	Bom Intento vs. Cupu	
Lake Cupu (9)	40±14	28.7±1.6	Bom Intento vs. Pereira	
Lake Pereira (48)	48±41	28.3±1.4	Cupu vs. Pereira	
Hemiodus unimaculatus (NP)				
Lake Bom Intento (25)	58±37	21.2±1.0	Bom Intento vs. Cupu	**
Lake Cupu (17)	85±42	20.1±2.3	Bom Intento vs. Pereira	
Lake Pereira (23)	50±25	20.6±3.2	Cupu vs. Pereira	**
Species caught in 2 Lakes	**Hg (ng/g wet weight)**	**Length (cm)**		**p**
Schizodon vittatum (NP)				
Lake Cupu (5)	125±92	25.1±4.8		
Lake Pereira (7)	130±114	27.3±3.0		
Curimata inornata (NP)	55±2	14.3±0.4		
Lake Bom Intento (2)	53±14	14.3±0.4		
Lake Cupu (2)				
Pygocentrus nattereri (P)				
Lake Bom Intento (4)	366±130	20.1±2.3		
Lake Pereira (8)	371±316	20.8±2.2		
Hoplias malabaricus (P)				
Lake Bom Intento (3)	178±77	26.4±8.8		*
Lake Pereira (4)	383±116	31.4±5.4		
Pellona castelnaeana (P)				
Lake Cupu (4)	466±89	33.5±4.4		
Lake Pereira (10)	488±265	35.4±1.3		

[a] NP = Non-predatory species; P = Predatory species, according to Ferreira et al. (1998).

Table 9 – Spatial variation of average Hg of key species caught when the waters were rising on the Tapajós River, 2001. The number of samples is shown in brackets (p < 0.05; ** p < 0.01 – Mann-Whitney test)*

Species caught in the 3 Lakes	**Hg (ng/g wet weight)**	**Length (cm)**	**Lakes compared**	**p**
Plagioscion squamosissimus (P)[a]				
Lake Bom Intento (7)	331±161	25.5±2.9	Bom Intento vs. Cupu	
Lake Cupu (4)	337±139	29.3±6.0	Bom Intento vs. Pereira	
Lake Pereira (42)	376±154	28.0±4.1	Cupu vs. Pereira	
Species caught in 2 Lakes	**Hg (ng/g wet weight)**	**Length (cm)**		**p**
Schizodon fasciatus (NP)				
Lake Bom Intento (4)	58±27	24.5±4.8		
Lake Pereira (4)	92±93	27.1±2.8		
Schizodon vittatum (NP)				
Lake Bom Intento (12)	43±11	26.9±2.4	*	
Lake Pereira (7)	35±23	27.8±3.2		
Curimata inornata (NP)				
Lake Bom Intento (35)	32±14	15.9±2.4		
Lake Pereira (26)	32±12	16.6±2.4		
Geophagus proximus (NP)				
Lake Bom Intento (6)	47±31	17.6±2.9		
Lake Pereira (5)	33±19	17.1±4.0		
Pygocentrus nattereri (P)				
Lake Bom Intento (8)	405±178	19.0±2.5		
Lake Pereira (5)	419±211	18.4±4.0		
Serrasalmus rhombeus (P)				
Lake Bom Intento (2)	106±64	15.0±3.5		
Lake Cupu (14)	122±54	13.9±3.2		

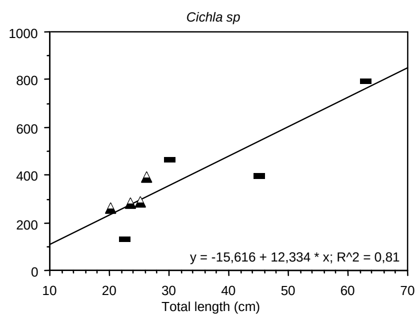
[a] NP = Non-predatory species; P = Predatory species, according to Ferreira et al.(1998).

The accumulation of Hg over the life cycle of some species

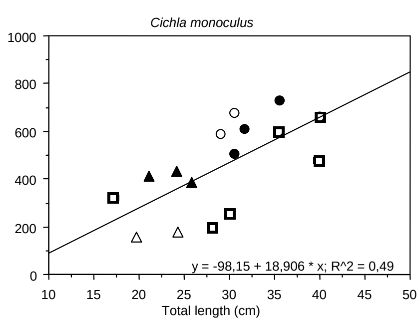
The graphs showing the accumulation of Hg over the life cycle of 25 species of fish from the Tapajós River can be seen in Figures 2 to 8. A positive linear or curvilinear relationship between Hg concentrations and the total length of the fish we studied was rarely observed. Only *Cichla monoculus* ($p=0.0002$) and *Cichla sp* ($p=0.0075$) clearly showed a positive linear accumulation of Hg as the length of the fish increased (Figure 2). For *Serrasalmus rhombeus* and *Semaprochilodus insignis*, a positive linear accumulation of Hg was also seen ($p<0.0001$ and $p=0.0002$, respectively), however our sample did not consider all classes of length that are characteristic of these two populations. The data suggest that positive non-linear accumulations of Hg during the development of *Ageneiosus brevifilis* (p=0.1226), *Raphiodon vulpinus* (p=0.2245) and *Hypostomus emarginatus* (p=0.1294) do occur, but the small number of sample specimens and the restricted size distribution are a considerable handicap when it comes to analyzing these data. For the four following species, *Pellona Castelnaeana* (p=0.01771), *Pygocentrus nattereri* (p=0.0146), *Cichla temensis* (p=0.0067) and *Satonoperca acuticeps* (p=0.0295), positive non-linear accumulations were identified, but respecting the statistical significance chosen, p<0.05, only the first three are represented at their population levels (Figure 3).

Key applicable to all the following figures: Lake Bom Intento (△ rainy season, ▲ river rising), Lake Cupu (○ rainy season, ● river rising) and Lake Pereira (□ rainy season, ■ river rising).

Hg (ng/g)



Hg (ng/g)



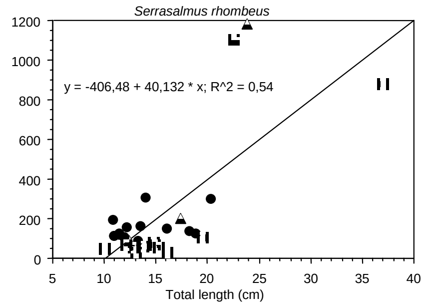
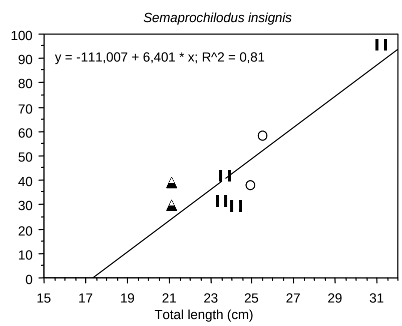
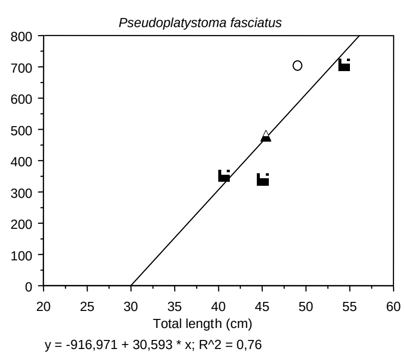


Figure 2 – Positive linear accumulation of mercury over the life cycle of the species





Hg (ng/g)

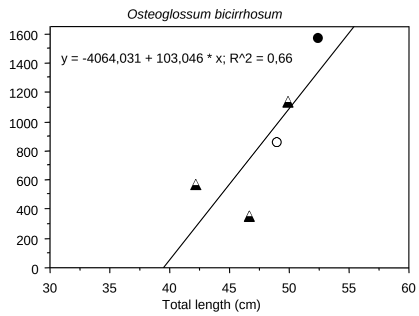


Figure 2 (continued) – Positive linear accumulation of mercury over the life cycle of the species

Hg (ng/g)

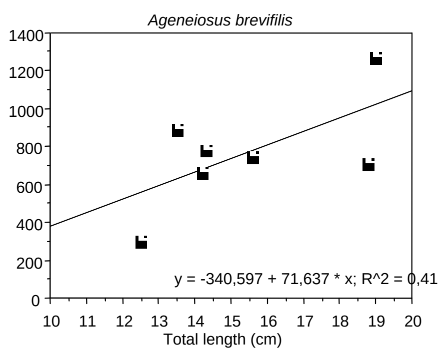
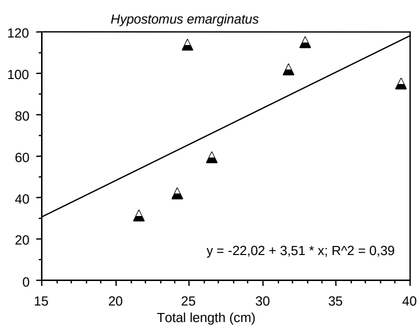
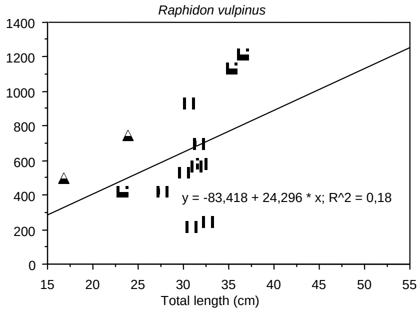


Figure 3 – Positive non-linear accumulation of mercury over the life cycle of the species

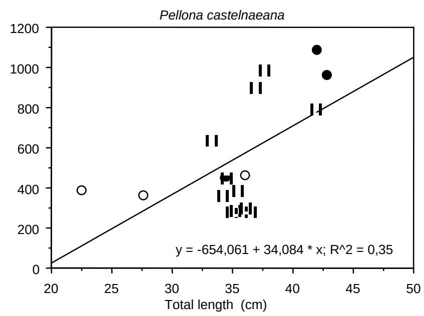
Hg (ng/g)



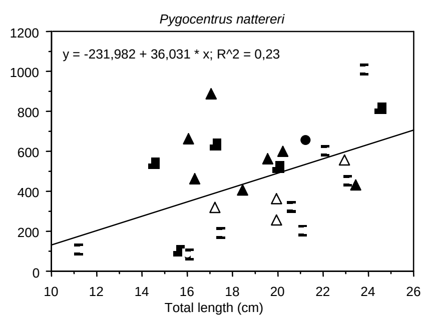
Hg (ng/g)



Hg (ng/g)



Hg (ng/g)



Hg (ng/g)

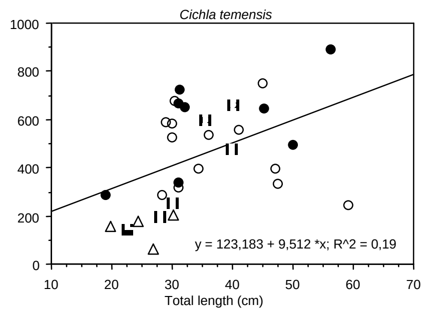


Figure 3 (continued) – Positive non-linear accumulation of mercury over the life cycle of the species

Hg (ng/g)

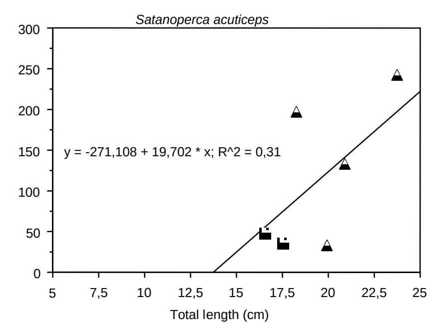
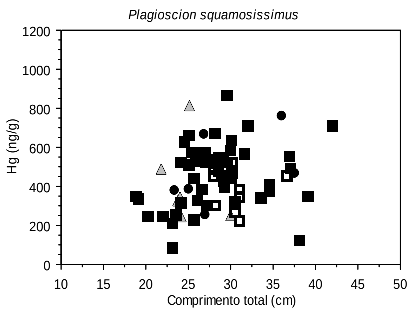


Figure 3 (continued) – Positive non-linear accumulation of mercury over the life cycle of the species

Various species of major importance in the local diet, such as *Plagioscion squamosissimus*, *Geophagus proximus*, *Curimata inornata*, *Potamorhina altamazonica*, *Mylossoma aureum*, *Metynnis argenteus*, *Triportheus albus* and *Serrasalmus eigenmanni* showed no variations in Hg levels related to the growth of the fish (Figure 4).



Hg (ng/g)

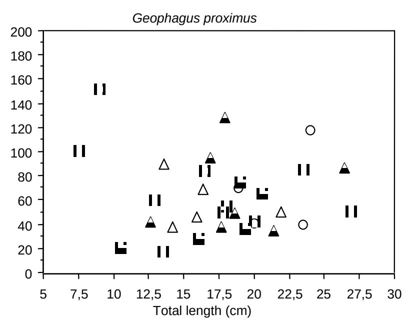
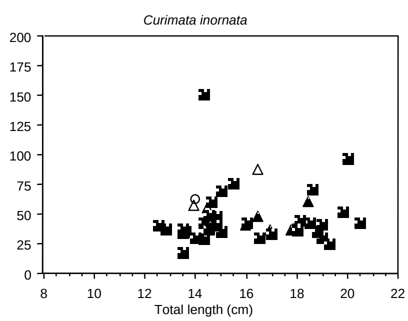
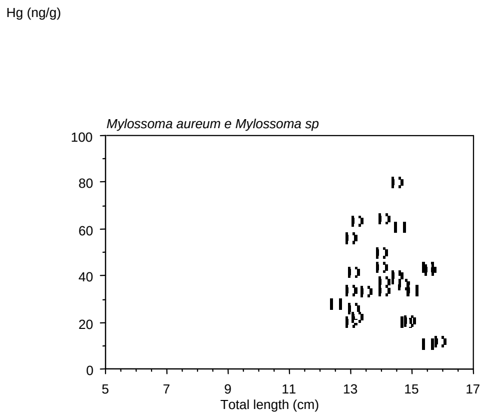
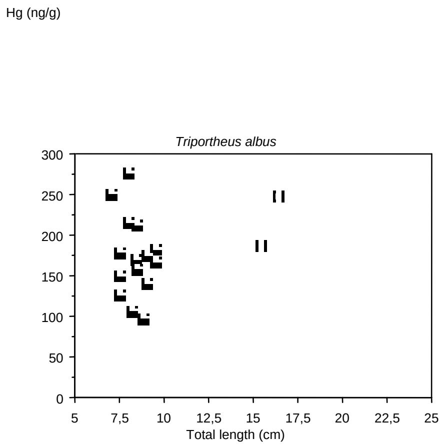


Figure 4 – Absence of correlation between the length of the fish and mercury concentrations over the life cycle of the species

Hg (ng/g)







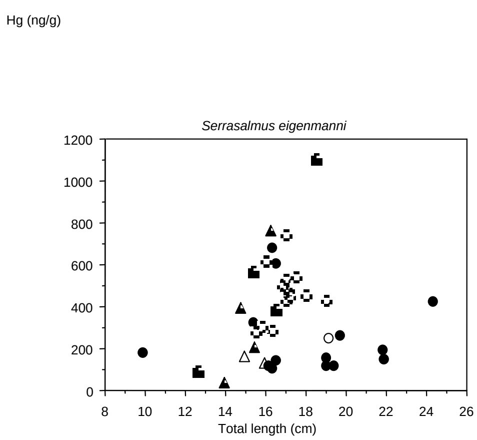
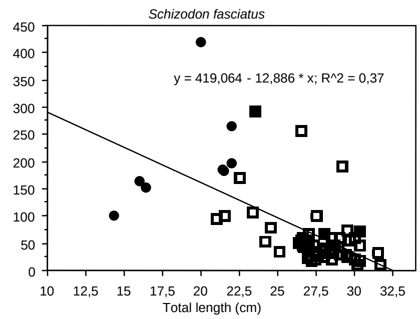


Figure 4 – (continued) – Absence of correlation between the length of the fish and mercury concentrations over the life cycle of the species

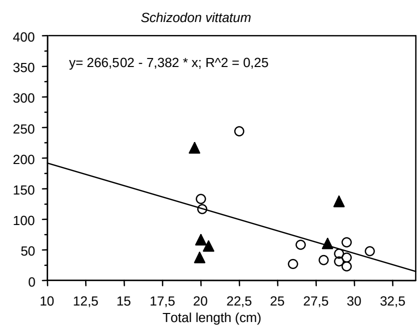
Schizodon vittatum, *Schizodon fasciatus* and *Leporinus friderici* presented negative non-linear accumulations of Hg over their respective life cycles (p=0.0144, p<0.0001 and p<0.0056, respectively) (Figure 5). *Hemiodus unimaculatus* showed a fall in Hg levels when it reached a length corresponding to its sexual maturity (R^2 = 0.42; p = 0.0011).

Below, individual adults present a positive non-linear accumulation of Hg (R^2 = 0.12; p = 0.0012) (Figure 6).

Hg (ng/g)



Hg (ng/g)



Hg (ng/g)

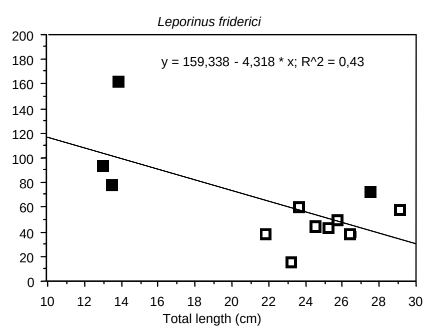


Figure 5 (continued) – Negative non-linear accumulation of mercury over the life cycle of the species

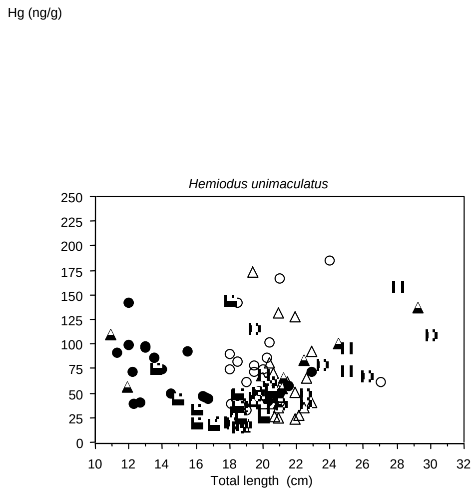


Figure 6 – Particular accumulation of mercury over the life cycle of the species

For *Hoplias malabaricus*, a curvilinear accumulation of Hg over the life cycle of this species was observed (p=0.0002) (Figure 7). For *Platydoras costatus*, a catfish that is little eaten by the population of the Amazon, but is sold as an ornamental fish, our data showed a negative linear Hg accumulation over the period of its development (p=0.00147) (Figure 8).

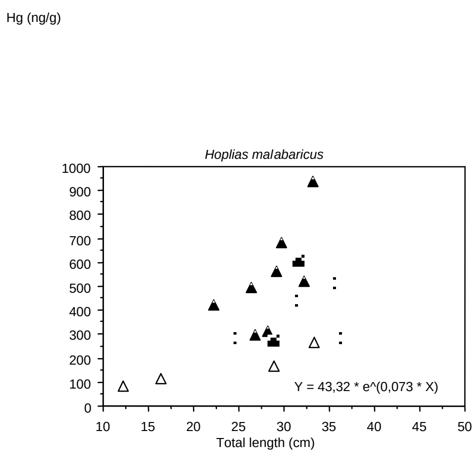


Figure 7 – Exponential accumulation of mercury over the life cycle of the species

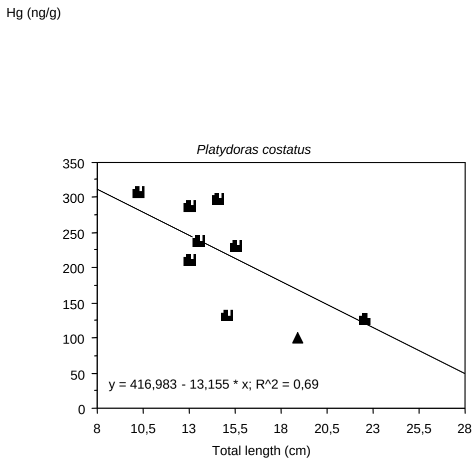


Figure 8 – Negative linear accumulation of mercury over the life cycle of the species

DISCUSSION

Fish are usually used as indicators of the quality of aquatic environments (HARRIS, 1995) and also to support estimates of the pollution levels of these ecosystems caused by the presence of anthropic activities (POVARI, 1995, MALM et al., 1990). Considering that various human activities are developed on a daily basis and in a predatory way in the Amazon, encouragement for carrying out research is essential in order to sustain all actions the aim of which is to limit the irreversible destruction of the environment and the quality of life of the local population.

The hydrological system of the lower Amazon suffers from significant cyclical variations, evidence of which can be seen in the rivers during the rainy season and the dry season. These temporal variations have an important roe to play in the productivity of aquatic ecosystems. They can also influence the dynamics of the ecosystems, the physiology of aquatic organisms, the bioavailability of Hg for the trophic network and consequently human exposure to this contaminant. Studies carried out on two riverbank populations of the Tapajós River (Brasília Legal and Cametá) clearly showed that Hg levels in the hair of individuals of these populations vary according to the seasons. The study done in Brasília Legal by Lebel et al. (1997) indicated that exposure to methylmercury was higher during the rainy season and another showed it was weaker in the dry season. However, Dolbec et al. (2001) showed the opposite situation for riverbank dwellers in Cametá. This divergence might be explained by the two populations eating different species of fish.

Our results clearly showed the biomagnification of Hg existing in non-predatory and predatory fish. This information agrees with the research carried our previously in the same region by Lebel et al. (1997) and Santos et al. (2000).

Hylander et al. (2000) identified a seasonal variation in Hg levels in three species of fish (*Pseudoplatystoma fasciatus*, *P.coruscans*, *Serrasalmus sp*) from the Pantanal wetlands. The highest concentrations were identified during the dry season. The authors associated this variation with a reduction in the level of the waters and the change of habitat observed during the dry season.

In work carried out in the Amazon temporal variations in the Hg levels of fish are generally not considered, despite knowing that the seasonal migration of fish introduces feeding variations that are not only temporal, but spatial also (GOULDING, 1980). These variations, associated with the sexual maturity phenomenon, might have a strong influence on the bioaccumulation of Hg over the year in a particular fish specimen or population. In a study carried out on the plains of the Ituqui River in the State of Pará, *Arapaima gigas* presented a seasonal variation that was opposite to the one observed by Hylander et al. (2000). During the dry season the average concentration of Hg in this species was more or less 50% lower than it was during the rainy season (CROSSA, 2001, personal communication). In our study no key species caught in Lake Bom Intento showed any temporal variation in the levels of Hg. On the other hand *Hemiodus unimaculus*, caught in Lake Cupu, showed higher levels of Hg during the rainy season compared to when the river is rising, while it was exactly the opposite in *Cichla temensis*. Higher levels of Hg during the rainy season in comparison with when the river is rising were also observed in *H. unimaculatus* and *Schizodon vittatum*, caught in Lake Pereira. These results differ from those of Sampaio da Silva et al. (2005), probably because the number of samples considered by these authors was significantly smaller than ours.

The specific dynamic of the region’s aquatic environments we studied, as a function of seasonal flooding, may cause modifications in the food the fish eat and/or facilitate the development of conditions that are favourable for the production of methylmercury. According to the study of Roulet et al. (2000) that was done on the lower Tapajós River, areas alongside water courses are important places for the production of methylmercury. In these sites the production and accumulation of methylmercury is closely linked to flooding and the decay of organic material.(Guimarães et al., 2000; Roulet et al., 2001). The three lakes we studied are different because of their respective physiographies (shape, size, surface area of bank zones that are flooded), how long they have been colonized for and the number of inhabitants they have. Despite this we identified no spatial variation of Hg levels in the muscle tissue of the fish of the majority of the species during the two samples. In research they did in Amapá Guimarães et al. (1999) compared Hg levels in sediment, in fish and in the populations living around two non-communicating lakes. In this study the two environments presented similar physiographic and geochemical characteristics, the only difference between them being a gold prospecting zone upstream from one of them. Concentrations of Hg in fish and in humans, which was high in the control lake, doubled in the disturbed lake. These authors suggest that this evidence should be checked and tested in other regions in the Amazon.

In the current research we observed five types of relationship between Hg levels and the total length of the fish described by Roulet and Maury-Branchet (2001). However, the models may not always apply to the same species. Furthermore, for *Hoplias malabaricus* and *Platydoras costatus*, we observed two new models of Hg bioaccumulation: exponential and negative linear. Roulet and Maury-Branchet (2001) identified a positive linear accumulation of Hg in *Raphidon vulpinus* and *Satanoperca acuticeps*, while our results suggest a positive non-linear accumulation. The lack of adult specimens (>36.0 cm) and juvenile specimens (<16.0 cm) in our sample might explain this difference. For many species, like *Pellona castelnaeana*, *Plagioscion squamosissimus*, *Mylossoma aureum*, *Curimata inornata*, *Schizodon fasciatus* and *S. vittatum*, the correlations between Hg levels and the total length of the fish are comparable in the two studies. On the other hand, the two authors suggest a positive linear model for *Pygocentrus nattereri*, while our data show a positive non-linear bioaccumulation of Hg. These same authors identified an absence of correlation between Hg concentrations and length in *H. emarginatus*, while we observed a positive non-linear correlation, despite the fact we had no juvenile specimens (<20.0 cm). The use of an interval of restricted lengths in the study of Roulet and Maury-Branchet (2001) may have given rise to this difference. In the current research only *Cichla monoculus*, *Cichla sp* and *Hoplias malabaricus* presented significant correlations of the linear and positive curvilinear type between the concentrations of Hg and the total length of the fish. The absence of this correlation in the majority of fish we studied may be associated with variety in the diet of the fish, their capacity to migrate and other aquatic environment factors, such as the specific dynamic, the levels of Hg in sediment, in organic material in suspension and in organisms like plankton and phytobenthos (LACERDA et al., 1988; REUTHER, 1994). Data corresponding to *S. rhombeus*, *S. insignis* and *O. bicirrhosum* also suggest significant linear type correlations, but the number of samples and the distribution of the sizes of fish do not allow us to draw any further conclusions (Figure 3).

It is important to emphasize that correlations between levels of Hg and the length of the fish are directly dependent on sampling, notably the collection of specimens that are representative of a given population. In this study we looked in particular at 25 species of common fish eaten in the region, of which only 18 are well represented at the level of their respective populations. Therefore we need to be careful, because it was not our intention to determine the total exposure to Hg of the local human population from eating fish. Another word of caution is also necessary, due to the complexity of the aquatic trophic networks of the Amazon, because of the diversity and density of its species, as well as the sensitive nature of these networks to the natural and anthropic changes to which they are subject (BOUDOU and RYBEIRE, 1997). Until now changes in the environmental factors and their influence on the fish populations have been little studied in the Amazon's ecosystems. Recent research in Arctic regions have shown that in lakes that have been disturbed by intense removal of vegetation (total clearing), concentrations of methylmercury in zooplankton were higher than those seen in zooplankton coming from lakes that had not been disturbed (GARCIAS and CARIGNAN, 1999). The authors attributed this difference to an increase in erosion and the leaching of fine material that was present in the areas cleared of vegetation; this facilitated the dispersion of organic material as dissolved organic carbon. In the Artic environment, high levels of carbon have an influence on the Hg methylation process and, therefore, on the feeding conditions of zooplankton. The importance of erosion in the transfer of the Hg naturally occurring in the soils of the Amazon to aquatic ecosystems has already been observed by Roulet et al. (1998a); Farella et al. (2001) and Farella (2005), but no relationship between this and the Hg seen in ichthyofauna has ever been established. Historically, there has never been any gold prospecting activity in the region we studied, therefore it is a priority zone in the current process of regional colonization. In this region the environmental impact of human activity is impressive. However, these anthropic disturbances have not been clearly translated into different levels of Hg in fish coming from the three ecosystems we studied.

CONCLUSION

In view of the importance of fish in the daily diet of those who live on the banks of the Tapajós River the levels of Hg observed in the muscle tissue of predatory fish are cause for concern. Temporal and spatial variations in Hg concentrations were not observed in the majority of species we studied. The results we obtained also suggest that the three aquatic ecosystems studied do not present specific different characteristics that might be responsible for differences in the availability of Hg for their respective trophic chains. From this research it is evident that the local species of fish from the Tapajós River have different ways of accumulating Hg over their life cycles. This being the case the different ways the fish accumulate Hg, as well as any possible spatial and temporal variations of the levels of this metal must be considered when educational measures are being taken to inform the exposed population of the issues involved here.

SPECIAL THANKS

This research depended on financial support from the CRDI-Canada, through its Caruso II Project, the Ministry of Education of Quebec and the GÉOTOP-UQÀM. The authors are equally grateful for the help of the fishermen of Lakes Bom Intento, Cupu and Pereira and the camp assistants. A special thanks to Isabelle Rhéault, Serge Paquet, Jean-Rémy D. Guimarães, Carlos José Passos and to the members of Cohema- Evandro Chagas Institute.

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Article received on 29.11.2005. Approved on 21.02.2006.