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Original Contribution

Mercury in Populations of River Dolphins of the Amazon and Orinoco Basins

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Abstract: In the Amazon and Orinoco basins, mercury has been released from artisanal and industrial gold mining since the Colonial time, as well as a result of deforestation and burning of primary forest, that release natural deposits of methyl mercury, affecting the local aquatic vertebrate fauna. This study reports the presence of mercury in river dolphins' genera *Inia* and *Sotalia*. Mercury concentrations were analysed in muscle tissue samples collected from 46 individuals at the Arauca and Orinoco Rivers (Colombia), the Amazon River (Colombia), a tributary of the Itenez River (Bolivia) and from the Tapajos River (Brazil). Ranges of total mercury (Hg) concentration in muscle tissue of the four different taxa sampled were: *I. geoffrensis humboldtiana* 0.003–3.99 mg kg⁻¹ ww ($n = 21$, $M_e = 0.4$), *I. g. geoffrensis* 0.1–2.6 mg kg⁻¹ ww ($n = 15$, $M_e = 0.55$), *I. boliviensis* 0.03–0.4 mg kg⁻¹ ww ($n = 8$, $M_e = 0.1$) and *S. fluviatilis* 0.1–0.87 mg kg⁻¹ ww ($n = 2$, $M_e = 0.5$). The highest Hg concentration in our study was obtained at the Orinoco basin, recorded from a juvenile male of *I. g. humboldtiana* (3.99 mg kg⁻¹ ww). At the Amazon basin, higher concentrations of mercury were recorded in the Tapajos River (Brazil) from an adult male of *I. g. geoffrensis* (2.6 mg kg⁻¹ ww) and the Amazon River from an adult female of *S. fluviatilis* (0.87 mg kg⁻¹ ww). Our data support the presence of total Hg in river dolphins distributed across the evaluated basins, evidencing the role of these cetaceans as sentinel species and bioindicators of the presence of this heavy metal in natural aquatic environments.

Keywords: Amazon, Bioindication, Gold mining, Mercury contamination, Orinoco, River dolphins

INTRODUCTION

The Amazon and Orinoco basins are home to the highest diversity of river dolphins on the planet (Mosquera-Guerra

Published online: November 12, 2019

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et al. 2018a, b, c), represented by the genera *Inia* (*I. geoffrensis*: *I. g. geoffrensis*, Amazon basin; *I. g. humboldtiana*, Orinoco basin; *Inia boliviensis* Mamore, Itenez, Grande and the upstream of the Madeira River, in Bolivia and Brazil; and *Inia araguaiaensis*, Tocantins and Araguaia basins) and *Sotalia* (*S. fluviatilis*, Amazon) (Caballero et al. 2007; Shostell and Ruiz-García 2010; Hrbek et al. 2014; Gravena et al. 2015; Mosquera-Guerra et al. 2018a). Species within the genus *Inia* are the largest river dolphins known, with more than 2 m (150–207 kg) of body size, and showing sexual dimorphism (da Silva 1994, 2009), while *S. fluviatilis* is the smallest species in the family Delphinidae, with an average body size of 1.5 m (35–55 kg) and no sexual dimorphism (da Silva 1994; Da Silva and Best 1994; Caballero et al. 2007).

Amazon River dolphins are considered top predators in freshwater ecosystems with a wide trophic spectrum (at least 43 species in 30 fish families); in average, adult river dolphins in the genus *Inia* consume 2.5–3.0 kg day⁻¹ (Best and da Silva 1989). These predators are intrinsically dependent on the flood pulse dynamics of the basin and its effect on the temporal and spatial distribution of their prey (Mosquera-Guerra et al. 2018b). Species in these two genera perform longitudinal migrations, with differential spatial ecology between males and females. Males can have displacements of more than 400 km (Mosquera-Guerra et al. 2018b), whereas females are philopatric, remaining in wetlands where they reproduce and take care of their offspring (Trujillo 2000; Mosquera-Guerra et al. 2018b). River dolphin pregnancy lasts between 12.3 and 13 months, with 3.62 and 4.56 years between births. They have only one offspring that reaches its maturity between 8 and 10 years, and with an average life span of 40 years (Martin and da Silva 2018).

As active top predators characterized by: (1) high feeding requirements; (2) a wide trophic spectrum of prey; (3) active behaviour; (4) extensive migrations; (5) high biomass; and (6) extended longevity, South American river dolphins are susceptible to exposure and ultimately accumulation of contaminants such as mercury. River dolphins are among the most threatened cetaceans on the planet (Reeves et al. 2003), and their natural habitats have been intensively affected by anthropogenic activities, such as gold mining, timber deforestation, agricultural expansion and, more recently (2000's), the construction of hydro-power dams, primarily in Bolivia, Brazil and Peru (Anderson et al. 2018). To date, there are 140 dams operating or under construction, as well as at least 428 planned dams

only for the Amazon basin (Forsberg et al. 2017; Latrubesse et al. 2017; Anderson et al. 2018; Mosquera-Guerra et al. 2018a). This has resulted in the presence of large amounts of chemical contaminants, including organochlorines and mercury (Barbosa et al. 1997; Boas-Villas 1997; Amorim et al. 2000; Bahía-Oliveira et al. 2004; Passos and Mergler 2008; Hacon et al. 2009). Changes in the biogeochemical cycles, associated with the transformation of these environments, have resulted in changes in the processes of bioaccumulation, biotransference and biomagnification of mercury in the food web of aquatic ecosystems (Porcella 1994; Morel et al. 1998; Ullrich et al. 2001; Sarica et al. 2005).

In this study, we document the presence of total Hg in wild populations of river dolphins through the analysis of this pollutant in muscle tissue samples of 46 individuals, including dead, stranded and captured and released animals. Samples were obtained as part of a remote-monitoring study at the Orinoco River (border between Colombia and Venezuela), the Amazon River in Colombia and Peru, the Itenez River in Bolivia and Tapajos River in Brazil. Samples from the Arauca River, in Colombia, were obtained from stranded individuals.

MATERIALS AND METHODS

Individuals, Collecting Localities and Tissues Collection

A total of 46 individuals were analysed, including: stranded and released individuals ($n = 8$, 17.39%); and captured and released animals ($n = 33$, 71.74%); as well as carcasses (dead individuals) found floating in the river ($n = 5$, 10.87%). Captures were associated with the deployment of transmitters as part of the Program of Satellite Monitoring of River Dolphins (Annex I); fieldwork spanned between 2015 and 2018. Sampling localities included the following sub-basins of the Amazon: Amazon River (Colombia, $n = 7$), Caballococha Lake (Peru, $n = 2$), San Martín River (Bolivia, $n = 8$) and Tapajos River (Brazil, $n = 8$); as well as at the Orinoco basin, in the Arauca River (Colombia, $n = 8$) and the Orinoco River (Colombia, $n = 13$) (Fig. 1).

Each individual was measured, its weight was recorded, and its stage of age was estimated based on body length following: Martin and da Silva (2018), da Silva (2009) and Da Silva and Best (1994) (“Appendix”), also including dead animals, since they were detected in general good

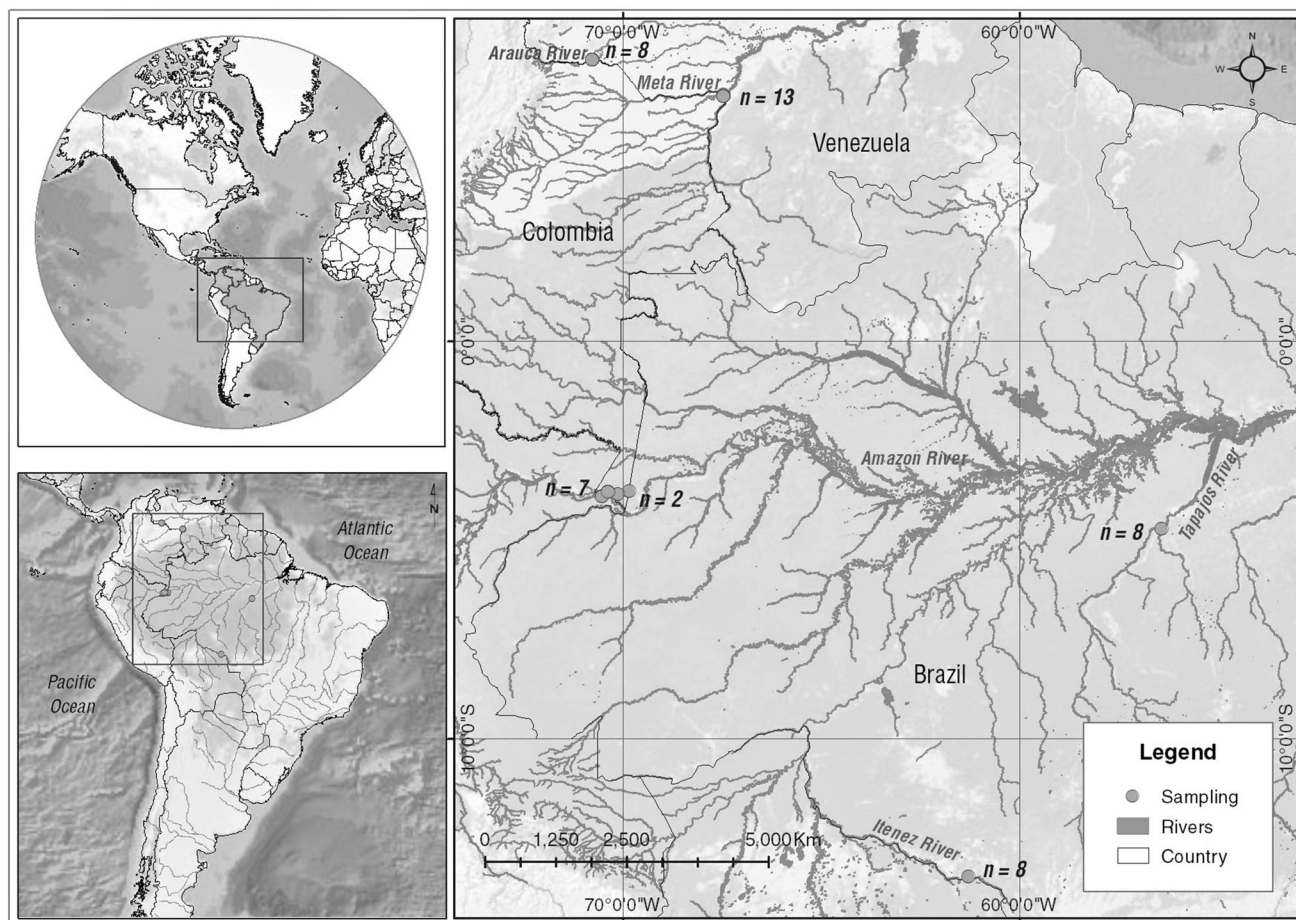


Figure 1. Locations where tissue samples were collected from river dolphins in the Amazon and Orinoco basins for mercury assessment.

conditions with a very low degree of decomposition of no more than 24 h after death. In addition, necropsies were performed in dead animals, according to protocols described in Geraci and Lounsbury (2003).

For each individual, we extracted between 1 and 2 g of muscle tissue, taken from the dorsal region under standard conditions; samples were divided into small pieces and stored at -4°C in plastic containers, previously washed in acid and taken for mercury assay, following protocols by Kuiken and Hartmann (1993).

Mercury Analysis

Once on the laboratory, samples were acidified and stored it in a refrigerator at approximately -4°C to prevent changes in volume due to evaporation (Eaton et al. 1998). To prevent contamination, sample containers and equipment were cleaned following the protocols of the Chemical Methods Manual for Fish and Seafoods (Canadian Food

Inspection Agency. Amend 4. 1999-16.2) (Eaton et al. 1998).

Dolphin tissue samples were pre-treated, through microwave-assisted acid digestion, following the methods proposed in the section 3030 K of the Chemical Methods Manual for Fish and Seafoods, procedure also implemented in Wei-Wei et al. (2006). Readings of contamination with Hg in dolphin tissue samples were performed following the spectrometric cold vapour atomic absorption standard method in the Chemical Methods Manual for Fish and Seafoods (Canadian Food Inspection Agency. Amend 4. 1999-16.2) (Eaton et al. 1998), on an iCE 3000 Series Atomic Absorption Spectrometer—Thermo Fisher Scientific. Approximately 1 g wet weight of tissue was dried in an oven to constant weight, as suggested by Siebert et al. (1999). The mercury detection limit was 0.003 mg kg^{-1} , and the mercury quantification limit was 0.1 mg kg^{-1} of dolphin muscle tissue; all concentrations were reported in grams per kilogram wet weight. The statistical analyses were also performed with values expressed as wet weight (ww).

No appreciable Hg contamination was detected in blanks. Tuna tissue was used as certified referenced material. Laboratory analyses for Hg did not include replicates, since we were only able to extract small amounts of tissue (< 2 g) from alive individuals that constitutes 89% ($n = 41$) of our samples ($n = 46$).

Statistical Analyses

The statistical analyses were carried out in R version 3.3 (R Core Team 2013). A Shapiro–Wilks test was conducted to account for data normality in data set (Hg concentration, dolphins' size and weight). According to this test, the Hg data were not adjusted to a normal distribution (P value: 2.6×10^{-16}). Hence, we performed a Mann–Whitney U test for comparing Hg concentration between females and males. Additionally, a Kruskal–Wallis test for multiple comparisons was performed to determined Hg level differences in dolphin tissues among basins (Amazonas, Orinoco and Itenez).

In order to determine the relationship between size and weight, we performed a linear correlation between these two variables for all analysed individuals (42 adults, two subadults and two newborns). Afterwards, we performed a linear correlation between: weight/length index (calculated for all individuals) and total Hg concentration for each taxon. Variables were log transformed before performing the statistical analyses.

Finally, we did a box plot of the variation in total Hg concentration by sex; and a second box plot, in order to compare Hg concentrations for *Inia* and *Sotalia fluviatilis* in our study and those reported for *S. guianensis* from the Brazilian Atlantic coast. A significance level of $\alpha = 0.05$ was adopted for all analyses, and the data are presented as median (Me), maximum and minimum values.

RESULTS

We report total Hg concentration from 46 dolphin individuals, discriminated as follows: *I. g. geoffrensis* ($n = 15$; 10 Males; 5 Females) from the Amazon basin in Colombia, Brazil and Peru; *I. g. humboldtiana* ($n = 21$; 14 Males; 7 Females), from the Orinoco basin in Colombia; *I. g. boliviensis* ($n = 8$; 7 Males; 1 Female), from the Itenez and San Martin Rivers in Bolivia; and *S. fluviatilis* ($n = 2$; 1 Male; 1 Female), from the Amazon River in Colombia (Table 1; “Appendix”).

We also documented a high variability in total Hg concentration values among analysed samples (taxonomic and geographic: basin and sub-basin). Mercury was detected in 100% of the analysed dolphins, with maximum values recorded for the genus *Inia*. *Inia. g. humboldtiana* was the subspecies with the highest individual total Hg concentration values documented in this study, recovered from a juvenile male ($3.99 \text{ mg kg}^{-1} \text{ ww}$) and an adult female ($3.50 \text{ mg kg}^{-1} \text{ ww}$), both from the Arauca River in the Colombian Orinoco. *Inia g. geoffrensis* had a maximum total Hg concentration value of $2.60 \text{ mg kg}^{-1} \text{ ww}$, in an adult male from the Tapajos River, Brazil. Interestingly, concentration values for *I. g. geoffrensis* from the Amazon basin in Colombia, and *I. boliviensis* from the San Martin River in the Bolivian Amazon, reported the lowest total Hg concentrations with values under $0.5 \text{ mg kg}^{-1} \text{ ww}$. Finally, *S. fluviatilis* presented a maximum total Hg concentration value of $0.87 \text{ mg kg}^{-1} \text{ ww}$, in a female from the Amacayacu River, in the Colombian Amazon (Table 1).

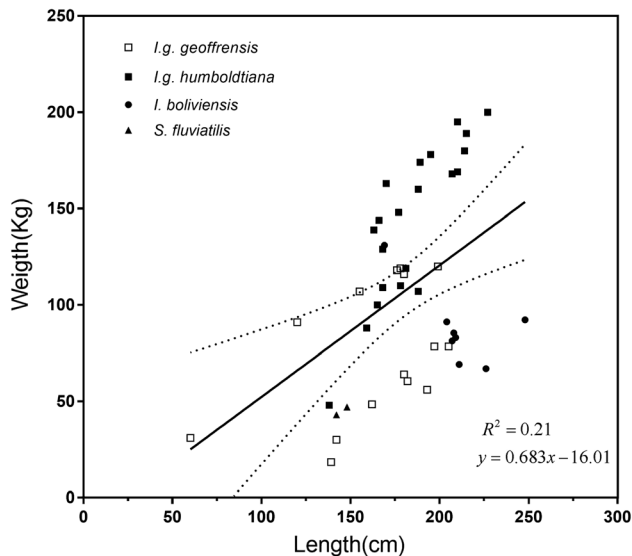
We report a weak linear correlation ($R^2 = 0.21$; P value = 0.00135), between size and weight among analysed individuals (42 adults, 91.30%, two subadults, 4.34%; and two newborns, 4.34%) (Fig. 2); as well as weak statistical support for a series of linear correlations between the weight/length index and total Hg concentration (F -statistic: 1.134; P value = 0.2927), for: (1) all the analysed taxa; (2) *I. g. geoffrensis*; (3) *I. g. humboldtiana*; and (4) *I. boliviensis*; (Fig. 3a–d, respectively). Since *S. fluviatilis* was represented by two individuals, we only report their position on the Cartesian plane (Fig. 3e).

The data for body size and weight were not normally distributed. We did not find statistically significant differences in body size and weight between males and females (Kruskal–Wallis Chi-squared = 0.18473, $df = 1$, P value = 0.6673; ANOVA: F value: 0.0103; P value = 0.749) (Fig. 4). Finally, we found no significant differences in total Hg levels among basins (Amazon, Orinoco and Itenez) (Kruskal–Wallis Chi-squared = 5.366, $df = 2$, P value = 0.06836; ANOVA P value = 0.749, respectively).

Although our results showed no relationship between total Hg concentration and body size (F -statistics = 2.122; P value = 0.1523), we found a significant (F -statistics 4.194; P value = 0.04656), but weak correlation ($R^2 = 0.087$) between Hg concentration and weight.

Table 1. Concentration of Total Hg in Muscle Tissue of River Dolphins (*Inia* and *Sotalia*) in the Amazon and Orinoco River Basins.

Taxa	Hg concentration (mg kg ⁻¹ wet weight)			Body length (cm)			
	Sex	Males	Females	All	Males	Females	All
<i>I. g. geoffrensis</i>	Median	0.55	0.5	0.55	179	162	178
	Maximum	2.6	1.6	2.6	205	199	205
	Minimum	0.1	0.1	0.1	60	120	60
	No. individuals	10	5	15	10	5	15
<i>I. g. humboldtiana</i>	Median	0.4	0.1	0.4	173.5	190	188
	Maximum	3.99	3.5	3.99	227	214	227
	Minimum	0.004	0.1	0.004	159	138	138
	No. individuals	14	7	21	14	6	20
<i>I. boliviensis</i>	Median	0.1	0.2	0.1	2.08	208.5	
	Maximum	0.4	0.2	0.4	248	226	248
	Minimum	0.03	0.2	0.03	169		
	No. individuals	7	1	8			
<i>Sotalia fluviatilis</i>	Value	0.87	0.1	0.67	142	148	148
	No. individuals	1	1	2	1	1	2

**Figure 2.** Linear correlation between size and weight among river dolphin individuals included in our samples.

DISCUSSION

Evidence of mercury in the aquatic ecosystem in the Amazon and Orinoco basins has been well documented since the 1980s (Martinelli et al. 1988; Lacerda 1997; Lacerda and Salomens 1998). The main source of this pollutant is gold extraction, mechanized, artisanal and industrial,

with an estimate of more than 200,000 tn deposited into aquatic ecosystems since Colonial time (Pfeiffer et al. 1989; Villas Bôas 1997; Bahía-Oliveira et al. 2004). Currently, the artisanal small-scale gold mining sector is considered the major consumer of Hg and also the main source of mercury emissions in Latin America and the Caribbean (UNEP/ROLAC 2014). Estimates for 2010 show that mercury released into the atmosphere worldwide by this sector accounted for 71% of the overall emissions, reaching 77% in South America (UNEP/ROLAC 2014). In the Amazon, 63% of the mercury was found to be released by activities related to gold mining (Roulet et al. 1998a, b, 2000; Artaxo et al. 2000; Guimaraes et al. 2000). For the Amazon, the amount of Hg released to the ecosystem by the gold mining sector was estimated at 3000 tn between 1987 and 1994, with an approximate average range between 100 and 200 tn year⁻¹ (Cid de Souza and Bidone 1994; Aula et al. 1994; Guimaraes et al. 1995; Palheta and Andrew 1995; Villas Bôas 1997; Kehrig et al. 1997; Lacerda 1997; Barbosa and Dorea 1998; Veiga et al. 1994, 1999; Veiga 1997).

Illegal gold mining is widespread in South America, and it is present in Brazil, in the: Tapajos (Roulet et al. 1998a, b; Dos Santos et al. 2000), Paraiba, Tocantins, Madeira, Xingu, Negro, Amapari, Solimões and Amazon

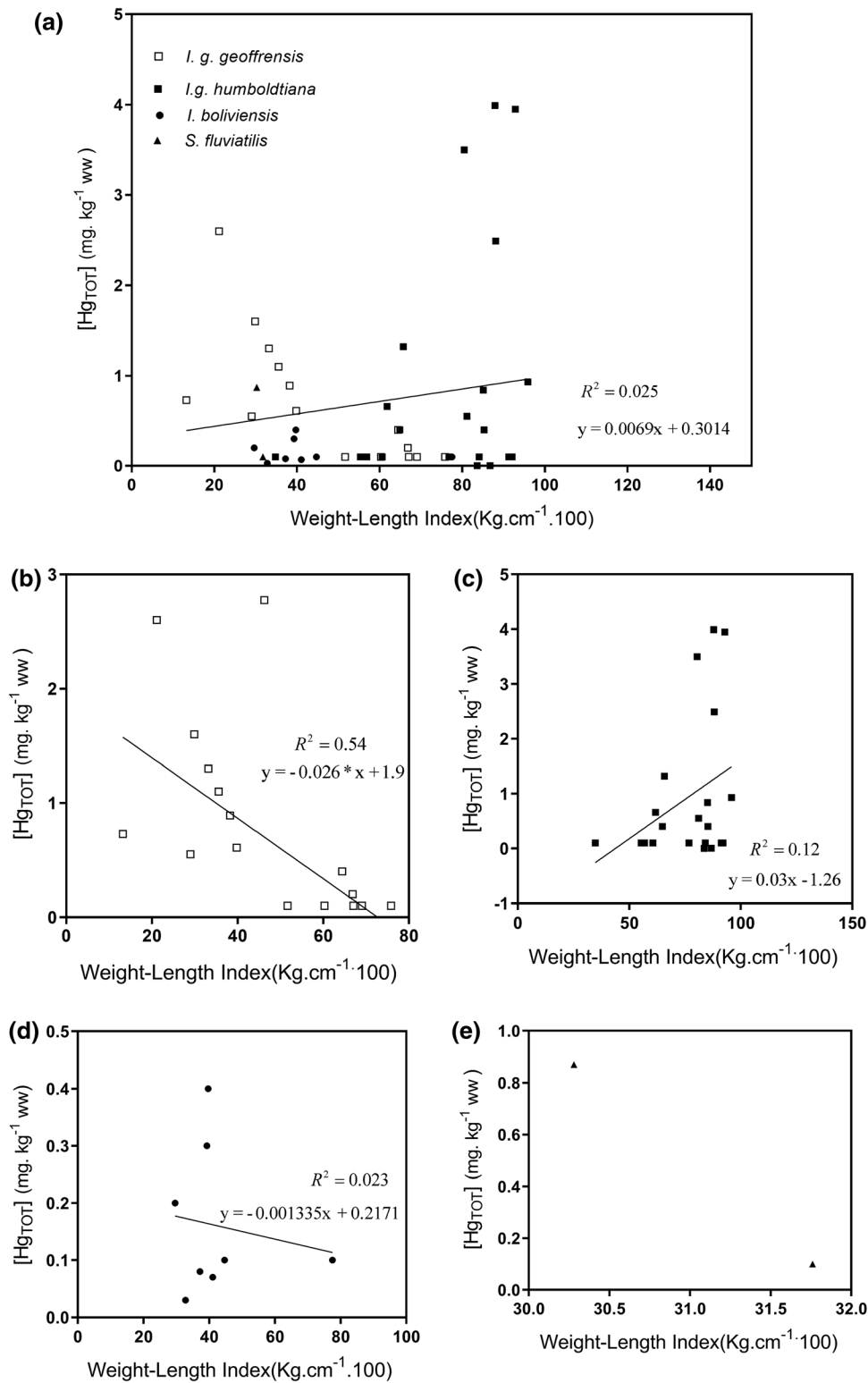


Figure 3. Linear correlation between weight/length index and total Hg concentration for: **a** all the analysed taxa; **b** *I. g. geoffrensis*; **c** *I. g. humboldtiana*; **d** *I. boliviensis*; and **e** the position of the two sampled individuals of *S. fluviatilis* on the Cartesian plane.

Rivers; in Bolivia, verified at the: Madeira, Beni and Itenez Rivers (Pouilly et al. 2013); in Colombia, at the Putumayo and Caqueta Rivers (Nuñez-Avellaneda et al. 2014); in

Ecuador, at Nambija River; and in French Guiana, along tributaries of the Negro River Basin (Barbosa and Dorea 1998) (Figs. 5, 6).

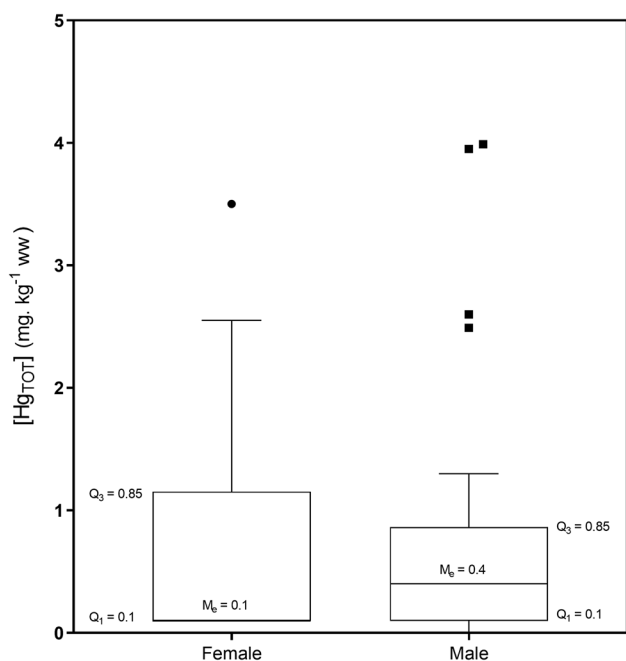


Figure 4. Box plot of the variation in total Hg concentration by sex and sampling locations.

Additionally, mercury also exists in the natural soil deposits in the Amazon Basin, and it is released into the aquatic environment through deforestation and burning, whereby the methylmercury bioaccumulates up the food chain (Souza Araujo et al. 2016). As a summary, 63% of the mercury entering the aquatic ecosystem is thought to be related to gold mining (Roulet et al. 1998a, b, 2000; Artaxo et al. 2000; Guimaraes et al. 2000), 31% from runoff from deforestation and 3% from atmospheric emissions from burning (Roulet et al. 1998a, b).

The presence of mercury in aquatic environments constitutes one of the major problems globally, affecting marine and continental ecosystems, such as the Amazon and Orinoco basins, with records of this contaminant in fish, otters and recently in river and coastal dolphins (Rosas and Lethi 1996; Dias Fonseca et al. 2005; Siciliano et al. 2008; Panebianco et al. 2011; Salinas et al. 2013; Nuñez-Avellaneda et al. 2014; Mosquera-Guerra et al. 2015a, b, c; Venturieri et al. 2017). Currently, high levels of mercury concentrations are a public health problem, with indigenous people and fishermen of the Tapajos and Teles Pires Rivers in the Brazilian Amazon having high levels of this contaminant, with values that exceeded the WHO safe limit (0.5 mg kg^{-1}), based on hair analyses (Dorea et al. 2005).

Wildlife is exposed primarily to methylmercury (MeHg) through their diet, rather than to other chemical forms of Hg, due to its persistence and high mobility within

the food web of aquatic ecosystems (Porcella 1994; Morel et al. 1998; O'Shea 1999; Ullrich et al. 2001; Sarica et al. 2005; Moura et al. 2012), primarily in the omnivorous and carnivorous levels, mostly affecting top predator species (Aula et al. 1994; Malm et al. 1995, 1997; Lebel et al. 1997; Evans et al., 1998; Basu et al. 2005; Sarica et al. 2005; Markert 2007; Molina et al. 2010; Bossart 2011).

Despite dolphins being considered the most effective top predators in the aquatic ecosystems of the Amazon and Orinoco basins (Gomez-Salazar et al. 2012), a role that they share with other mammalian species such as otters, as well as carnivorous reptiles and fish (Trujillo 2000), we only statistically test for biomagnification of total Hg in our data on dolphin's weight. We failed in finding a correlation between total Hg concentration and body size, due to differences in adult individual's body size. Among river dolphins, differences in body size can be found at: (1) the genus level (*Inia* and *Sotalia*); (2) among species and subspecies of *Inia* (*I. g. geoffrensis*, *I. g. humboldtiana* and *I. boliviensis*); and even (3) at the population level, such as *I. g. geoffrensis* which proved to be smaller in the Tapajos River than in the Amazon River (da Silva 2009). However, all the analysed individuals in this work presented high concentrations of total Hg in their tissues, in agreement with data reported in Rosas and Lethi (1996), who showed evidence of the presence of this heavy metal in maternal milk of *I. g. geoffrensis* from Manaus (Brazil); as well as data in Mosquera-Guerra et al. (2015b) that confirmed the presence of this pollutant in muscle tissues in stranded individuals of *I. g. humboldtiana* (Arauca, Orinoco) and *I. g. geoffrensis* (Amazon).

Sotalia guianensis distributed along the Brazilian Atlantic coast are also affected by the presence of mercury. High concentrations of this heavy metal have also been evidenced in populations from Rio de Janeiro State, with values ranging between 1.07 ± 0.35 ($0.2\text{--}1.66 \mu\text{g g}^{-1} \text{ ww}$) in the muscle tissue of 20 individuals (Moura et al. 2011); Amazon coast: 0.4 ± 0.16 ($0.07\text{--}0.79 \mu\text{g g}^{-1} \text{ ww}$, $n = 27$) (Moura et al. 2012); Northern Rio de Janeiro State: $0.98 \mu\text{g g}^{-1} \text{ ww}$, $n = 21$ (Kehrig et al. 2009) and 0.73 ($0.34\text{--}1.42 \mu\text{g g}^{-1} \text{ ww}$), $n = 20$ (Carvalho et al. 2008); Espirito Santo State: $1.8 \pm 0.46 \mu\text{g g}^{-1} \text{ ww}$, $n = 5$ (Lopes et al. 2008) and Guanabara Bay: 0.7 ($0.2\text{--}2.5 \mu\text{g g}^{-1} \text{ ww}$), $n = 15$ (Kehrig et al. 2004), evidencing the wide distribution of this pollutant throughout the basin and its high mobility in the aquatic trophic networks (Sarica et al. 2005) (Fig. 7).

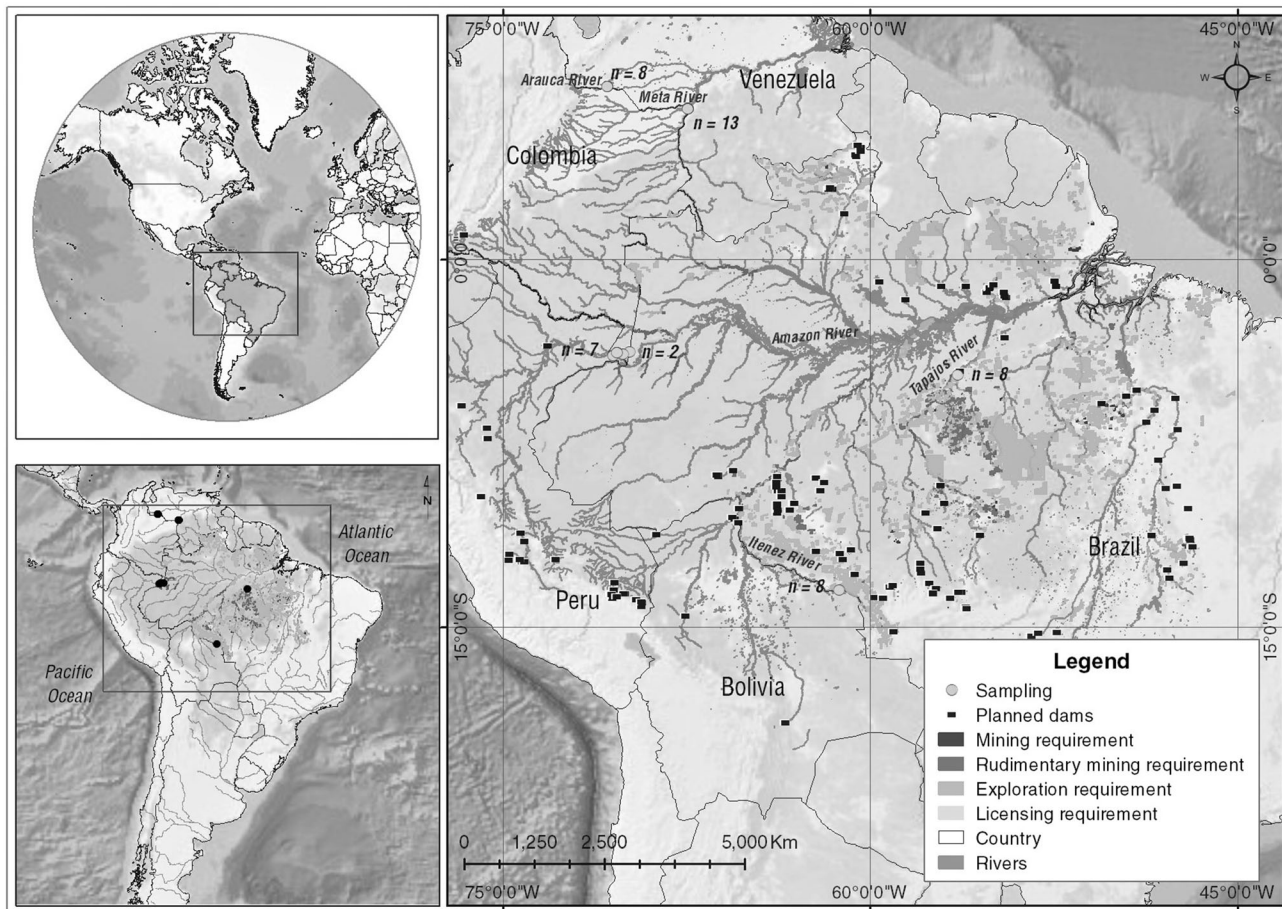


Figure 5. Current gold mining operations in the Amazon and Orinoco basins and the locations where river dolphins were sampled. Adapted from WCS (2017).

As mentioned, the presence of mercury is not only restricted to dolphin populations. Data on mercury concentration from muscle tissue samples among other Amazon aquatic vertebrates are presented in Nuñez-Avellaneda et al. (2014), in which the presence of total mercury was evaluated in muscle tissue samples of eleven fish species at four locations in the Colombian Amazon, reporting values that ranged between 0.0116 and 2.0123, $M_e = 0.3549$ mg kg⁻¹ Hg. Additionally, Mosquera-Guerra et al. (2015a) reported that 54% ($n = 103$) of the total tissue samples, of the catfish species *Calophysus macropterus* (omnivore) from the Amazon, presented ranges between: 0.11 and 1.66 mg kg⁻¹, coinciding with that in Salinas et al. (2013) for the same cat fish species. Data on Hg concentrations from muscle tissue samples in other Amazon aquatic top mammals predator include: the giant otter (*Pteronura brasiliensis*), from Rio Negro in the Pantanal, Brazil, with a mean mercury concentration 0.17 mg g⁻¹ in muscle tissue samples in the Amazon (Dias Fonseca et al. 2005).

In the southern Atlantic Ocean, Marcovecchio et al. (1990) reported values of mercury concentration of 3.8 µg g⁻¹ ww in liver tissues for the same region, in one female of the Franciscan dolphin. Similar results are reported in Asian coastal and riverine dolphins by Wei-Wei et al. (2006) in some key tissues: liver 87.94 (1.4–181 µg g⁻¹ ww), kidney 21.8 (43 µg g⁻¹ ww), small intestine 17.04 (2.4–66 µg g⁻¹ ww) and stomach 2.65 (0.65–5.2 µg g⁻¹ ww) of five Yangtze finless porpoises (*Neophocaena phocaenoides asiaeorientalis*) in Eastern Dongting Lake, China; Zhou et al. (1993) document concentrations of total Hg for *N. p. sunameri* in: liver 10.24 (0.31–34.7 µg g⁻¹ ww) and kidney 1.735 (0.756–3.01 µg g⁻¹ ww) for populations distributed in the Yellow Sea (China); Zhang et al. (1996) in the same species reported total Hg concentrations for: liver 76.05 (0.23–34.93 µg g⁻¹ ww), kidney 8.23 (0.06–29.93 µg g⁻¹ ww), small intestine 0.36 (0.06–1.46 µg g⁻¹ ww) and stomach 0.54 (0.00–1.96 µg g⁻¹ ww) in the Bohai Sea (China); Fujise et al. (1988) reported concen-

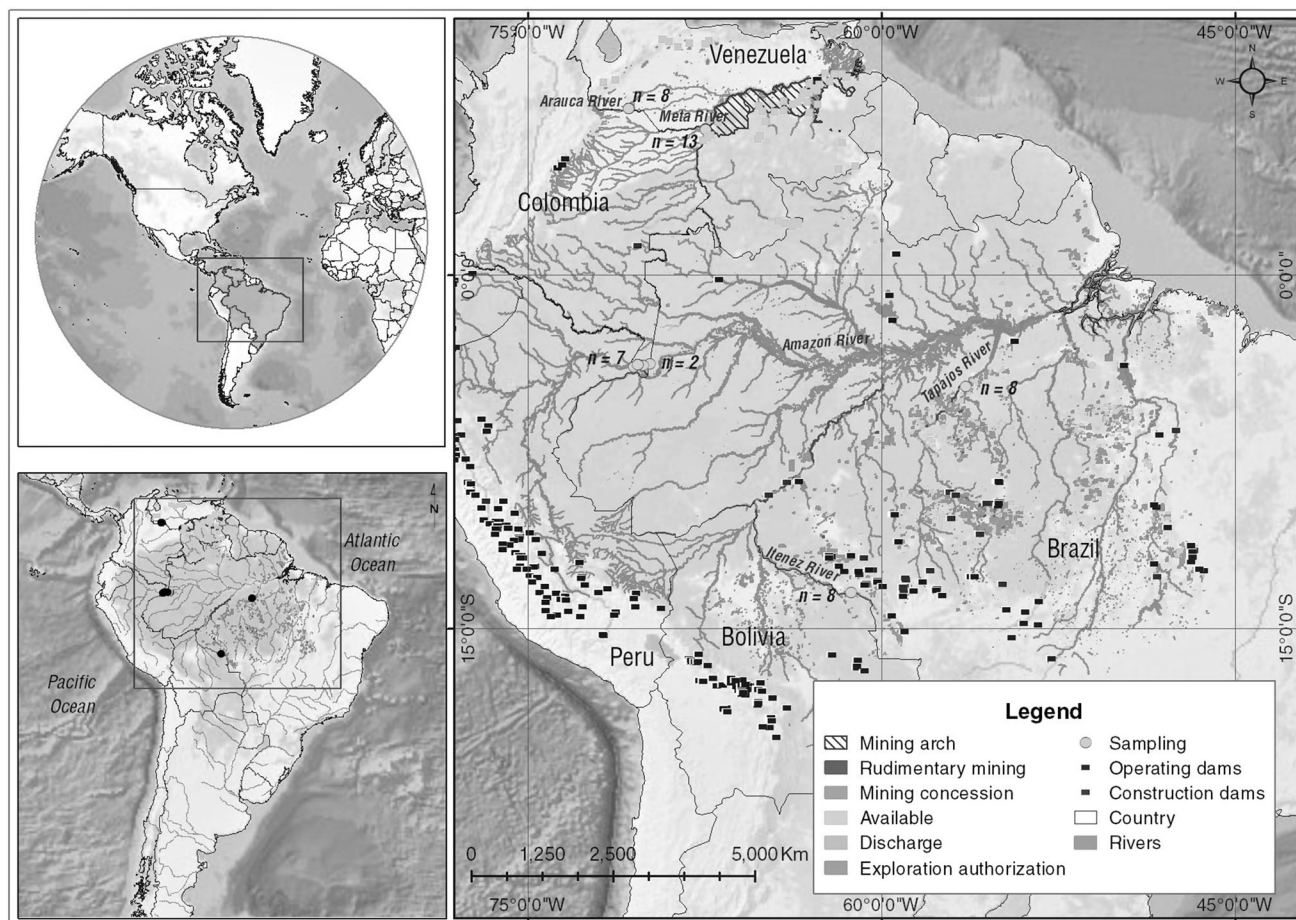


Figure 6. Projected gold mining operations in the Amazon and Orinoco basins and the locations where river dolphins were sampled. Adapted from WCS (2017).

trations values in liver ($3.38 \mu\text{g g}^{-1}$ ww) and kidney ($1.8 \mu\text{g g}^{-1}$ ww), in populations of *Phocoenoides dalli* for in the Pacific Northwest, and Yang (2001) reported concentration values of 7.8 (2.31 – $28.8 \mu\text{g g}^{-1}$ ww) in liver, for the same species, obtained from populations of the Japan Sea. Additionally, in North Eastern Europe, Siebert et al. (1999) reported concentrations of total Hg in: liver 12.1 (0.2 – $13.0 \mu\text{g g}^{-1}$ ww) and kidney 2.3 (0.1 – $33.5 \mu\text{g g}^{-1}$ ww) for 60 individuals of *Phocoena phocoena*, distributed in the North and Baltic Seas.

The presence of mercury in aquatic environments affects mammalian species at several levels (Scheuhammer et al. 2007). Mercury is known to be at least partially responsible for the decline of North American otters (*Lutra canadensis*) and the European otter (*Lutra lutra*) (Evans et al. 1998; Gutleb et al. 1998; Wren 1985). Although incidents of Hg poisoning in wild mammals are rare, this is

perhaps a result of the practitioner's inability to observe and demonstrate the impacts, rather than an absence of the disease (Wren 1986).

Effects of the mercury on dolphins are documented by Krishna et al. (2003), with Atlantic bottlenose dolphins (*Tursiops truncatus*) having liver abnormalities associated with chronic accumulation of Hg. Cardellicchio et al. (2002) reported that a synergy between Hg with other pollutants could result in the death of striped dolphins (*Stenella coeruleoalba*) found in the Mediterranean coasts; primary damage was caused to the central nervous system, including a motor and sensory deficit and behavioural deficiency, anorexia, lethargy, reproductive disorders and death of foetuses as well as deficiencies of the immune system, facilitating the appearance of infectious diseases and pneumonia. High concentrations of mercury also generated serious disorders in liver, kidney and brain tis-

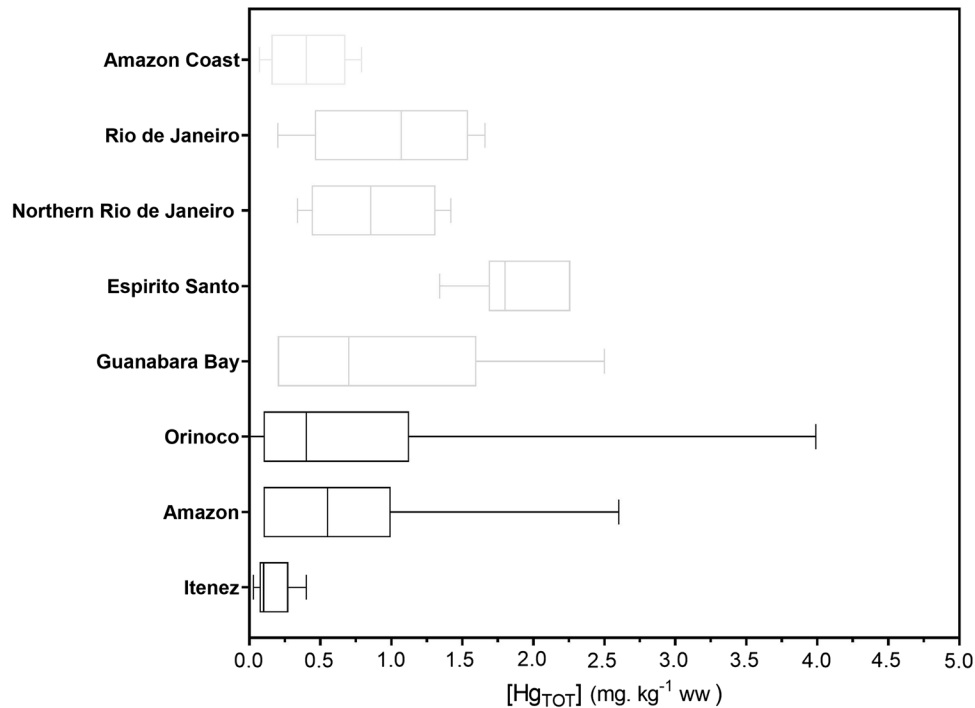


Figure 7. Box plot of total Hg concentrations ($\mu\text{g g}^{-1}$ ww) in muscle tissues of *S. guianensis* from the Brazilian Atlantic coast: Guanabara Bay (Kehrig et al. 2004); Espirito Santo (Lopes et al. 2008); Northern Rio de Janeiro State (Carvalho et al. 2008); Rio de Janeiro (Moura et al. 2011); Amazon coast (Moura et al. 2012); *Inia* and *Sotalia* from Amazon, Orinoco and Itenez Rivers in the present study.

sues of striped dolphins (Augier et al. 1993). Although effects caused by high concentrations of Hg have not been studied yet, mercury is present in river dolphins since very early stages of development. Mosquera-Guerra et al. (2015b) reported the presence of Hg in a river dolphin foetus (0.16 mg kg^{-1} wet weight) collected in the Amazon.

Freshwater dolphins are sensitive to environmental perturbation, evidencing specific responses to changes in their habitats and rendering them useful bioindicators for monitoring the health of riverine ecosystems (Ichihashi and Tatsukawa 1993; Aguilar et al. 1999; O'Shea 1999; Gomez-Salazar et al. 2012). It is urgent to generate information on the effects of mercury bioaccumulation on populations of river dolphins. To date, no studies have been conducted on the effects of this pollutant on *Inia* and *Sotalia*, raising the concern for the persistence of species in these two genera. This is particularly true, if we take into consideration the increment in intensity and frequency of other types of threats affecting these cetaceans, a situation that elevated *Inia*'s conservation status from Data Deficient up to Endangered (Da Silva et al. 2018).

CONCLUSIONS

Our data support the presence of total Hg in river dolphin tissues in the Amazon, Itenez and Orinoco basins, evidencing the role of these cetaceans as bioindicators of the presence of this heavy metal in natural aquatic environments.

These results indirectly point towards the complexity of the Hg biogeochemical cycle in the analysed environments and call our attention on the need to incorporate other factors, such as mercury measurements at different levels of the trophic web, as well as elements of movement ecology of these cetaceans in future analyses. River dolphins are keystone species in the South American largest river basins, making it critical to address this growing threat through transboundary cooperation among countries towards reducing the use of mercury, as stated in the Minamata Convention. Mercury contamination further exacerbates the conservation status of these aquatic mammals, populations of which are currently experiencing the negative effects of habitat degradation and fragmentation, due to the construction of hydropower dams, conflicts with fisheries and the effects of climate change.

Additional studies to evaluate *Inia* and *Sotalia* conservation status under these emergent scenarios are urgent, particularly for the middle and lower Amazon basin. In this context, it is necessary to extend this type of analysis along the main tributary rivers such as Caqueta/Japura, Putumayo/Iça, Madeira, the lower Amazon basin and the Araguaia–Tocantins complex.

The dolphins' position as top predators makes these organisms sentinel species of water resources. Therefore, changes in their health should be interpreted as an early warning on ecosystem degradation and even human health and wellbeing. The two analysed basins are homeland to some vulnerable sectors of the human population, which constitute ancestral fish-eating societies that face an imminent risk. This last statement should be interpreted under the philosophy of the sustainable development goals in which “no one is left behind”.

ACKNOWLEDGEMENTS

This research was conducted as part of the South America River Dolphins Conservation Program, sponsored by the Whitley Fund for Nature, the Foundation Segré, and Colciencias (National Doctorate Scholarship 785). This program is part of the strategic plan of the South American River Dolphins Initiative (SARDI), supported by WWF in Brazil, Colombia, Peru, Ecuador and Bolivia. Special gratitude to S. Usma, D. Amoroch, D. Willems, K. Berg, L. Sainz, J. Rivas, J. L. Mena, J. Surkin, and M. Wulms from the WWF network. The authors would also like to express their gratitude to the fishing communities and the local and national authorities who collected stranded animals and supported the capture of river dolphins in the framework of the satellite tracking program of river dolphins in the Amazon and Orinoco River basins.

APPENDIX

See Table 2.

Table 2. Concentration of Total Hg in River Dolphin (*Inia* and *Sotalia*) in the Amazon and Orinoco River Basins Analysed in Muscle Tissue (mg kg⁻¹ ww).

Taxon	Localities	Basin	Hg (mg kg ⁻¹ wet weight)	Sex	Sample origin	LT (cm ⁻¹)	Weight (kg ⁻¹)	Collection date
<i>I. g. geoffrensis</i>	Puerto Nariño (Colombia)	Amazon	0.2	M	T/A	178	119	07 July 2015
<i>I. g. geoffrensis</i>	Puerto Nariño (Colombia)	Amazon	0.1	M	T/N	60	31	13 January 2016
<i>I. g. geoffrensis</i>	Puerto Nariño (Colombia)	Amazon	0.1	F	D/A	120	91	04 March 2017
<i>I. g. geoffrensis</i>	Puerto Nariño (Colombia)	Amazon	0.1	M	T/A	176	118	04 March 2017
<i>I. g. geoffrensis</i>	Puerto Nariño (Colombia)	Amazon	0.1	F	T/A	199	120	10 November 2017
<i>I. g. geoffrensis</i>	Cabalococha (Perú)	Amazon	0.1	F	D/A	155	107	10 November 2017
<i>I. g. geoffrensis</i>	Cabalococha (Perú)	Amazon	0.4	M	D/A	180	116	04 March 2017
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	1.1	F	T/A	180	64	07 October 2017
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	0.73	M	T/SA	139	18.4	07 October 2017
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	2.6	M	T/SA	142	30	08 October 2017
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	0.61	M	T/A	197	78.4	08 October 2017
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	1.6	F	T/A	162	48.4	10 October 2017
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	1.3	M	T/A	182	60.4	10 October 2017
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	0.89	M	T/A	205	78.4	11 October 2017

Table 2. continued

Taxon	Localities	Basin	Hg (mg kg ⁻¹ wet weight)	Sex	Sample origin	LT (cm ⁻¹)	Weight (kg ⁻¹)	Collection date
<i>I. g. geoffrensis</i>	Tapajos River (Brasil)	Amazon	0.55	M	T/A	193	56	11 October 2017
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	1.32	F	S/A	181	119	13 January 2017
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	0.66	F	S/A	178	110	04 March 2017
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	0.4	M	S/A	1.68	109	04 March 2017
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	0.1	M	S/A	165	100	04 March 2017
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	3.99	M	S/A	215	189	04 March 2017
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	0.93	M	S/A	170	163	04 March 2017
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	3.5	F	S/A	210	169	04 April 2015
<i>I. g. humboldtiana</i>	Arauca (Colombia)	Orinoco	0.1	M	S/A	168	129	04 March 2017
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.1	M	T/A	159	88	04 March 2017
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	2.49	M	T/A	227	200	04 March 2017
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.4	M	T/A	163	139	04 March 2017
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.004	M	T/A	166	144	06 January 2016
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.003	M	T/A	177	148	06 January 2016
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.84	M	T/A	188	160	06 January 2016
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	3.95	M	T/A	2.1	195	28 January 2018
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.1	F	T/A	195	178	09 November 2017
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.1	M	T/A	189	174	28 January 2018
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.1	F	T/A	214	180	28 January 2018
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.55	M	T/A	207	168	28 January 2018
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.1	F	T/A	188	107	28 January 2018
<i>I. g. humboldtiana</i>	Puerto Carreño (Colombia)	Orinoco	0.1	F	T/N	98	48	28 January 2018
<i>I. boliviensis</i>	Itenez River (Bolivia)	Itenez	0.1	M	T/A	169	131	1 November 2017
<i>I. boliviensis</i>	San Martin River (Bolivia)	Itenez	0.1	M	T/A	204	91.2	1 November 2017
<i>I. boliviensis</i>	San Martin River (Bolivia)	Itenez	0.08	M	T/A	248	92.25	1 November 2017
<i>I. boliviensis</i>	San Martin River (Bolivia)	Itenez	0.4	M	T/A	209	83	1 November 2017
<i>I. boliviensis</i>	San Martin River (Bolivia)	Itenez	0.07	M	T/A	208	85.4	1 November 2017
<i>I. boliviensis</i>	San Martin River (Bolivia)	Itenez	0.03	M	T/A	211	69.2	1 November 2017
<i>I. boliviensis</i>	San Martin River (Bolivia)	Itenez	0.2	F	T/A	226	67	2 November 2017
<i>I. boliviensis</i>	San Martin River (Bolivia)	Itenez	0.3	M	T/A	207	81.3	3 November 2017
<i>Sotalia fluviatilis</i>	Puerto Nariño (Colombia)	Amazon	0.1	F	D/A	148	47	13 January 2017
<i>Sotalia fluviatilis</i>	Amacayacú (Colombia)	Amazon	0.87	M	D/A	142	43	04 March 2017

Nomenclature for the origin of samples: captures for transmitter deployment (T); stranded animals (S); dead animals (D). Age of the individuals: adult (A) and newborns (N).

REFERENCES

- Aguilar A, Borrel A, Pastor T (1999) Biological factors affecting variability of persistent pollutant levels in cetaceans. *Journal Cetacean Research Management* 1:83–116
- Amorim MIM, Mergler D, Bahia MO, Dubeau H, Miranda D, Lebel J, Burbano RR, Lucotte M (2000) Cytogenetic damage related to low-levels of methylmercury contamination in the Brazilian Amazon. *Anais da Academia Brasileira de Ciências* 72: 497–507; <https://doi.org/10.1590/s0001-3765200000400004> [Online December 15, 2000]
- Anderson EP, Jenkins CN, Heilpern S, Maldonado-Ocampo JA, Carvajal-Vallejos FM, Encalada AC, Rivadeneira JF, Hidalgo M, Cañas CM, Ortega H, Salcedo N, Maldonado M (2018) Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Sci. Adv.* 4 (1), ea01642.
- Artaxo P, Calixto de Campos R, Fernandes T, Martins JV, Xiao Z, Lindqvist O, Fernández-Jiménez MT, Maenhaut W (2000) Large scale mercury and trace element measurements in the Amazon basin. *Atmospheric Environment* 34: 4085–4096; [http://doi.org/10.1016/s1352-2310\(00\)00106-0](http://doi.org/10.1016/s1352-2310(00)00106-0) [Online January 1, 2000]
- Augier H, Park WK, Ronneau C (1993) Mercury Contamination of the Striped Dolphin *Stenella coeruleoalba* Meyen from the French Mediterranean Coast. *Marine Pollution Bulletin* 26:306–311; [https://doi.org/10.1016/0025-326x\(93\)90572-2](https://doi.org/10.1016/0025-326x(93)90572-2) [Online June 1, 1993]
- Aula I, Braunschweiler H, Leino T, Malin I, Porvari P, Hatanaka T, Lodenius M, Juras A (1994) Levels of mercury in the Tucuruí Reservoir and its surrounding area in Pará, Brazil. In: *Mercury Pollution: Integration and Synthesis*, Watras CJ, Huckabee JW (Editors.), Boca Raton, Lewis Publishers, pp. 21–40
- Bahía-Oliveira M, Corvelo CC, Mergler D, Burbano RR, Lima PDL, Cardoso PC, Lucotte M, Amorim IM (2004) Environmental biomonitoring using cytogenetic endpoints in a population exposed to mercury in Brazilian Amazon. *Environmental and Molecular Mutagenesis* 44:346–349; <https://doi.org/10.1002/em.20054> [Online October 8, 2004]
- Barbosa CA, García AM, De Souza JR (1997) Mercury contamination in hair of riverine populations of Apiaçás Reserve in the Brazilian Amazon. *Water, Air, and Soil Pollution* 97(1–2): 1–8; <https://doi.org/10.1023/a:1018336820227> [Online June 1, 1997]
- Barbosa AC, Dorea JG. (1998) Indices of mercury contamination during breast feeding in the Amazon Basin. *Environmental Toxicology and Pharmacology* 6. 71–79; [https://doi.org/10.1016/s1382-6689\(98\)00031-3](https://doi.org/10.1016/s1382-6689(98)00031-3) [Online October 1, 1998]
- Basu N, Scheuhammer A, Grochowina N, Klenavic K, Evans O'Brien M, Chan HM (2005) Effects of mercury on neurochemical receptors in wild river otters (*Lontra canadensis*). *Environmental Science and Technology* 39: 3585–3591; <http://doi.org/10.1021/es0483746> [Online March 22, 2005]
- Best RC and da Silva VMF (1989) Amazon River dolphin, boto *Inia geoffrensis* (de Blainville, 1817). In: *Handbook of marine mammals*, Vol. 4: River dolphins and the larger toothed whales, Ridgway SH and Harrison R (editors), London: Academic Press, pp 1–24
- Boas-Villas RC (1997) The mercury problem in the Amazon due to gold extraction. *Journal of Geochemical Exploration* 58: 217–222; [https://doi.org/10.1016/s0375-6742\(96\)00075-1](https://doi.org/10.1016/s0375-6742(96)00075-1) [Online April 1997]
- Bossart GD (2011) Marine Mammals as Sentinel Species for Oceans and Human Health. *Veterinary Pathology* 48(3) 676–690; <https://doi.org/10.1177/0300985810388525> [Online December 15, 2010]
- Caballero S, Trujillo F, Vianna JA, Barrios-Garrido H, Montiel MG, Beltran-Pedrerros S, Marmontel M, Santos MCO, Rossi-Santos MR, Santos FR, Baker CS (2007) Taxonomic status of the genus *Sotalia*: species level ranking for ‘tucuxi’ (*Sotalia fluviatilis*) and ‘costero’ (*Sotalia guianensis*) dolphins. *Marine Mammal Science* 23(2): 358–386. <https://doi.org/10.1111/j.1748-7692.2007.00110.x> [Online June 15, 2007]
- Cardellicchio N, Decataldo A, Di Leo A, Giandomenico S (2002) Trace elements in organs and tissues of striped dolphins (*Stenella coeruleoalba*) from the Mediterranean Sea (Southern Italy). *Chemosphere* 49:85–90; [https://doi.org/10.1016/s0045-6535\(02\)00170-4](https://doi.org/10.1016/s0045-6535(02)00170-4) [Online October 01, 2002]
- Carvalho CEV, Di Benedetto APM, Souza CMG, Ramos RMA, Resende CE (2008) Heavy metal distribution in two cetacean species from Rio de Janeiro State, south-eastern Brazil. *J Mar Biol Assoc UK* 88:1117; <https://doi.org/10.1017/s002531540800325> [Online August 01, 2008]
- Cid de Souza TM, Bidone ED (1994) Estimativa do consumo global de mercúrio nos garimpos do estado do Pará, 1980–1993. SC: Camboriú, pp 32–33
- Da Silva VMF (1994) Aspects of the biology of the Amazonian dolphins Genus *Inia* and *Sotalia fluviatilis*. Ph.D. thesis, University of Cambridge, Cambridge, U.K, pp 327
- Da Silva VMF (2009) Amazon River Dolphin (*Inia geoffrensis*). In: *Encyclopedia of Marine Mammals*, Perrin WF, Wursig B, Theewissen JGM (editors), London, UK: Academic Press, pp 26–28
- Da Silva VMF, Best RC (1994) Tucuxi *Sotalia fluviatilis* (Gervais, 1853). In: *Handbook of marine mammals*, Volume 5 The first book of dolphins, Ridgway SH, Harrison R (editors) London, UK: Academic Press, pp 43–69
- Da Silva V, Trujillo F, Martin A, Zerbini AN, Crespo E, Aliaga-Rossel E, Reeves R (2018) *Inia geoffrensis*. The IUCN Red List of Threatened Species 2018: e.T10831A50358152. <https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T10831A50358152.en> [Online Marzo 21, 2018]
- Dias Fonseca FR, Malmb O, Waldemarin HF (2005) Mercury levels in tissues of Giant otters (*Pteronura brasiliensis*) from the Rio Negro, Pantanal, Brazil. *Environmental Research* 98: 368–371; <https://doi.org/10.1016/j.envres.2004.11.008> [Online January 21, 2005]
- Dorea JG, Souza JR, Rodrigues P, Ferrari I, Barbosa AC (2005) Hair mercury (signature of fish consumption) and cardiovascular risk in Munduruku and Kayabi Indians of Amazonia. *Environmental Research* 97:209–19; <https://doi.org/10.1016/j.envres.2004.04.007> [Online February 01, 2005]
- Dos Santos LSN, Müller RCS, Sarkis JES, Alves CN, Brabo ES, Santos EO, Bentes MHS (2000) Evaluation of total mercury concentrations in fish consumed in the municipality of Itaituba, Tapajós River basin, Pará, Brazil. *Science of the Total Environment* 261: 1–8; [https://doi.org/10.1016/s0048-9697\(00\)00590-8](https://doi.org/10.1016/s0048-9697(00)00590-8) [Online October 01, 2000]
- Eaton AD, Clesceri LS, Greenberg AE, Franson MAH (1998) *Standard methods for the examination of water and wastewater*. 20th ed. Washington, DC: American Public Health Association, American Water Works Association and Water Environment Federation.
- Evans RD, Addison EM, Villeneuve JY, MacDonald KS, Joachim DG (1998) An examination of spatial variation in mercury concentrations in otter (*Lutra canadensis*) in south-central

- Ontario. *Science of the Total Environment* 213: 239–245 [Online June 10, 1998]
- Forsberg BR, Melack JM, Dunne T, Barthem RB, Goulding M, Paiva RCD, Sorribas MV, Silva UL Jr, Weisser S (2017) The potential impact of new Andean dams on Amazon fluvial ecosystems. *PLoS ONE* 12(8): e0182254; <https://doi.org/10.1371/journal.pone.0182254> [Online August 23, 2017]
- Fujise Y, Honda K, Tatsukawa R, Mishima S (1988) Tissue distribution of heavy metal in Dall's porpoise in the northwestern Pacific. *Marine Pollution Bulletin* 19:226–230
- Geraci JR, Lounsbury VJ (2003) *Marine mammals ashore: a field guide for strandings, 2nd ed.*, Baltimore, MD: National Aquarium in Baltimore
- Gomez-Salazar C, Coll M, Whitehead H (2012) River dolphins as indicators of ecosystem degradation in large tropical rivers. *Ecological Indicators*, 23:19–26; <https://doi.org/10.1016/j.ecolind.2012.02.034> [Online December 01, 2012]
- Gravena W, da Silva VMF, da Silva MNF, Farias IP, Hrbek T (2015) Living between rapids: genetic structure and hybridization in botos (Cetacea: Iniidae: *Inia* spp.) of the Madeira River, Brazil. *Biological Journal of the Linnean Society*. 114, 4 -1. 764–777. <https://doi.org/10.1111/bij.12463> [Online January 22, 2015]
- Guimaraes JDR, Malm O, Pfeiffer WA (1995) Simplified radiochemical technique for measurement of net mercury methylation rates in aquatic systems near gold mining areas, Amazon, Brazil. *Science of the Total Environment*: 151–162; [https://doi.org/10.1016/0048-9697\(95\)04911-8](https://doi.org/10.1016/0048-9697(95)04911-8) [Online December 11, 1995]
- Guimaraes JDR, Meili M, Hylander LD, De Castro e Silva E, Roulet M, Narvaez-Mauro J.B, Alves de Lemos R (2000) Mercury net methylation in five tropical flood plain regions of Brazil: high in the root zone of floating macrophyte mats but low in surface sediments and flooded soils. *Science of the Total Environment*. 261. 99–107; [https://doi.org/10.1016/S0048-9697\(00\)00628-8](https://doi.org/10.1016/S0048-9697(00)00628-8) [Online October 01, 2000]
- Gutleb AC, Kranz A, Nechay G, Toman A (1998) Heavy metal concentrations in livers and kidneys of the pttter (*Lutra lutra*) from Central Europe. *Bull. Environmental Contamination and Toxicology*., 60: 273–279; <https://doi.org/10.1007/s001289900621> [Online February 01, 1998]
- Hacon S, Barrocas PRG, Vasconcellos ACS, Barcellos C, Wasserman JC, Campos RC (2009) Um panorama dos estudos sobre contaminação por mercúrio na Amazonia Legal no período de 1990 a 2005 avanças e lacunas. *Geochimica Brasiliensis* 23:029–048; <https://doi.org/10.21715/gb.v23i1.293> [Online June 15, 2009]
- Hrbek T, da Silva VMF, Dutra N, Gravena W, Martin AR, Farias IP (2014) A new species of river dolphin from Brazil or: how little do we know our biodiversity. *PLoS ONE* 9. 1. e83623; <https://doi.org/10.1371/journal.pone.0083623> [Online March 01, 1993]
- Ichihashi H, Tatsukawa R (1993) Heavy metals and organochlorine residues in Ganges river dolphins from India. *Marine Pollution Bulletin*, 26(3), 159–162; [https://doi.org/10.1016/0025-326x\(93\)90128-7](https://doi.org/10.1016/0025-326x(93)90128-7) [Online January 22, 2014]
- Kehrig HA, Malm O, Akagi H (1997) Methylmercury in hair samples from riverine groups, Amazon, Brazil. *Water, Air and Soil Pollution*.97: 17–29; <https://doi.org/10.1007/bf02409641> [Online June 01, 1997]
- Kehrig HA, Seixas TG, Baeta A, Lailson-Brito J, Moreira I, Malm O (2004) Total mercury, methylmercury and selenium in the livers and muscle of different fishes and a marine mammal from a tropical estuary-Brazil. *RMZ-Materials and Geoenvironment* 51:1111–1114; <https://doi.org/10.1007/s11356-008-0038-8> [Online August 27, 2008]
- Kehrig HA, Fernandes KWG, Malm O, Seixas TG, Di Benedetto APM, Souza CMM (2009) Transferência trófica de mercúrio e selênio na costa norte do Rio de Janeiro. *Quim Nova* 32:1822–1828. <https://doi.org/10.1590/s0100-40422009000700026> [Online January 01, 2009]
- Krishna D, Virginie D, Stéphane P, Jean-Marie B (2003) Heavy metals in marine mammals. In: *Toxicology of Marine Mammals*, Vos JV, Bossart GD, Fournier MI, O'Shea T (Editors.), London: CRC Press, pp 135–167
- Kuiken T, Hartmann, MG (Eds) (1993) *Cetacean pathology: dissection techniques and tissue sampling*. European Cetacean Society Newsletter 17:1–39
- Lacerda LD (1997) Evolution of mercury contamination in Brazil. *Water Air, and Soil Pollut* 97: 247–255; <https://doi.org/10.1007/bf02407463> [Online July 01, 1997]
- Lacerda LD, Salomens W (1998) Mercury from Gold and Silver Mining: A Chemical Time Bomb. *Springer-Verlag*, *International Journal of Surface Mining, Reclamation and Environment* 13:2; <https://doi.org/10.1080/09208119908944205> [Online April 27, 1998]
- Latrubesse EM, Arima EY, Dunne T, Park E, Baker VR, d'Horta FM, Wight C, Wittmann F, Zuanon J, Baker PA, Ribas CC, Norgaard RB, Filizola N, Ansar A, Flyvbjerg B, Stevaux JC (2017) Damming the rivers of the Amazon basin. *Nature* 546(7658): 363–369; <https://doi.org/10.1038/nature22333> [Online June 14, 2017]
- Lebel J, Roulet M, Mergler D, Lucotte M, Larribe F (1997) Fish diet and mercury exposure in a riparian amazonian population. *Water Air, and Soil Pollut*. 97, 31–44; <https://doi.org/10.1007/bf02409642> [Online June 01, 1997]
- Lopes AP, Vidal LG, Andrade-Costa ES, Schilithz PF, Barbosa LA, Bianchi I, Azevedo AF, Dorneles PR, Malm O, Lailson-Brito J (2008) Concentrações de mercúrio total em tecidos de cetáceos costeiros do estado do Espírito Santo. 8th Reunion de Trabajo de Especialistas en Mamíferos Acuáticos de America del Sur (13–17 October), Montevideo, Uruguay.
- Malm O, Castro MB, Bastos WR, Branches FJP, Branches JRD, Guaimares CE, Zufo EC, Pfeiffer WC (1995) An assessment of Hg pollution in different gold mining areas, Amazon, Brazil. *Science of the Total Environment*, 17:127–140; [https://doi.org/10.1016/0048-9697\(95\)04909-6](https://doi.org/10.1016/0048-9697(95)04909-6) [Online December 01, 1995]
- Malm O, Guimares JRD, Castro MB, Bastos WR, Viana JP, Pfeiffer WC (1997) Follow-up of mercury levels in fish, human hair and urine in the Madeira and Tapajós basins, Amazon, Brazil. *Water Air, and Soil Pollut*, 97: 45–51; <https://doi.org/10.1007/bf02409643> [Online June 01, 1997]
- Marcovecchio JE, Moreno VJ, Bastida RO, Gerpe MS, Rodriguez DH (1990) Tissue distributions of heavy metals in small cetaceans from the southwestern Atlantic Ocean. *Marine Pollution Bulletin* 21: 299–304; [https://doi.org/10.1016/0025-326x\(90\)90595-y](https://doi.org/10.1016/0025-326x(90)90595-y) [Online June 15, 1990]
- Markert B (2007) Definitions and principles for bioindication and biomonitoring of trace metals in the environment. *Journal of Trace Elements in Medicine and Biology, Suppl* 1:77–82; <https://doi.org/10.1016/j.jtemb.2007.09.015> [Online November 21, 2007]
- Martin AR, da Silva VMF (2018) Reproductive parameters of the Amazon river dolphin or boto, *Inia geoffrensis* (Cetacea: Ini-

- idae); an evolutionary outlier bucks no trends, *Biological Journal of the Linnean Society*: 123: 666–676; <https://doi.org/10.1093/biolinnean/bly005> [Online February 21, 2018]
- Martinelli LA, Ferreira JR, Forsberg BR, Victoria RL (1988) Mercury contamination in the Amazon – a gold rush consequence. *Ambio*: 17:252–254 [Online December 10, 1998]
- Molina CI, Gibon FM, Duprey JL, Domínguez E, Guimarães JR, Roulet M (2010) Transfer of mercury and methylmercury along macroinvertebrate food chains in a floodplain lake of the Beni River, Bolivian Amazonia. *Science of the Total Environment*. 408(16): 3382–3391; <https://doi.org/10.1016/j.scitotenv.2010.04.019> [Online July 15, 2010]
- Morel FMM, Kraepiel AML, Amyot M (1998) The chemical cycle and bioaccumulation of mercury. *Annual Reviews of Ecology and Systematics* 29, 543–566. Vol. 29:543–566; <https://doi.org/10.1146/annurev.ecolsys.29.1.543> [Online November 15, 1998]
- Mosquera-Guerra F, Trujillo F, Díaz-Granados MC, Mantilla Meluk H (2015a) Conservación de delfines de río (*Inia geoffrensis* y *Sotalia fluviatilis*) en los ecosistemas acuáticos de la Amazonia y Orinoco en Colombia. *Momentos de Ciencia*. 12 (2): 77–86 [Online July 15, 2015]
- Mosquera-Guerra F, Trujillo F, Caicedo-Herrera D, Martínez-Callejas S (2015b) Indicios de biomagnificación de Mercurio total (Hg) en las especies del género *Inia* (Cetartiodactyla: Iniidae) en los s Amazonas y Orinoco (Colombia). *Momentos de Ciencia* 12 (2): 145–149 [Online July 15, 2015]
- Mosquera-Guerra F, Trujillo F, Caicedo-Herrera D, Zoque-Cancelado J, Mantilla Meluk H (2015c) Impactos de las pesquerías de *Calophysus macropterus* un riesgo para la salud pública y la conservación de los delfines de río en Colombia. *Momentos de Ciencia* 12 (2): 88–99 [Online July 15, 2015]
- Mosquera-Guerra F, Trujillo F, Parra CA, Carvajal-Castro JD, Mantilla-Meluk H (2018a) Aspectos poblacionales y biogeográficos de la tonina o delfín de río, *Inia geoffrensis humboldtiana* Pilleri & Gihl, 1978 (Cetartiodactyla, Iniidae) en los ríos Guayabero y Losada, sierra de La Macarena, Meta, Colombia. Pp. 289–305. In: Lasso, CA, Morales- Betancourt MA and Escobar-Martínez, ID (Eds.). V. Biodiversidad de la sierra de La Macarena, Meta, Colombia. Parte I. Ríos Guayabero medio, bajo Losada y bajo Duda. Serie Editorial Fauna Silvestre Neotropical. Bogotá D.C., Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt [Online February 25, 2019]
- Mosquera-Guerra F, Trujillo F, Danni P, Oliveira-da-Costa M, Marmontel M, Armenteras-Pascual D, Usma S, Willems D, Carvajal-Castro JD, Mantilla- Meluk H, Franco N, Amorocho D, Maldonado R, Berg K, Sainz L, Van Damme PA, Cambell E (2018b) Analysis of distribution of river dolphins (*Inia* and *Sotalia*) in protected and transformed areas in the Amazon and Orinoco basins. Scientific Committee/Meetings/SC67B] Slovenia 2018/SM.
- Mosquera-Guerra F, Trujillo F, Oliveira-da-Costa M, Marmontel M, Armenteras-Pascual D, Usma S, Willems D, Carvajal-Castro JD, Mantilla-Meluk H, Franco N, Amorocho D, Maldonado R, Berg K, Sainz L, Van Damme PA (2018c) Movements and habitat use of river dolphins (Cetartiodactyla: Iniidae) in the Amazon and Orinoco river basins, determined from satellite tagging. Scientific Committee/Meetings/SC67B] Slovenia 2018/SM.
- Moura JF, Hacon SS, Vega CM, Hauser-Davis RA, Campos RC, Siciliano S (2011) Guiana dolphins (*Sotalia guianensis*, Van Beneden 1864) as indicator of the bioaccumulation of total Mercury along the coast of Rio de Janeiro State, Southeastern Brazil. *Bulletin of Environmental Contamination and Toxicology* 88:54–59; <https://doi.org/10.1007/s00128-011-0448-z> [Online October 20, 2011]
- Moura JF, Emin-Lima R, Hacon SS, Vega CM, Campos RC, Siciliano S (2012) Mercury Status of the Amazon Continental Shelf: Guiana Dolphins (*Sotalia guianensis*, Van Beneden 1864) as a Bioindicator. *Bulletin of Environmental Contamination and Toxicology* 89:412–418; <https://doi.org/10.1007/s00128-012-0663-2> [Online May 08, 2012]
- Núñez-Avellaneda M, Agudelo Córdoba E, Gil- Manrique BD (2014) Un análisis descriptivo de la presencia de mercurio en agua, sedimento y peces de interés socioeconómico en la Amazonia Colombiana. *Revista Colombia Amazónica* No 7: 149–159 [Online August 15, 2012]
- O’Shea TJ (1999) Environmental contaminants and marine mammals. In: *Biology of marine mammals*, Reynolds JM, Rommel SA (editors), Washington DC: Smithsonian Institution Press, pp 485–564
- Palheta D, Andrew T (1995) Mercury in environmental and biological samples from a gold mining area in the Amazon region of Brazil. *The Science of the Total Environment* 168: 63–69 [Online May 09, 1995]
- Panebianco MV, Negri MF, Botté SE, Marcovecchio JE, Cappozzo HL (2011) Metales pesados en el riñón del delfín franciscana, *Pontoporia blainvillei* (Cetacea: Pontoporiidae) y su relación con parámetros biológicos. *Latin American Journal of Aquatic Resources*. 39(3): 526–533; <https://doi.org/10.3856/vol39-issue3-fulltext-12> [Online November 01, 2011]
- Passos CJS, Mergler D (2008) Human mercury exposure and adverse health effects in Amazon: a review. *Cadernos de Saúde Pública* 24:S503–S520
- Pfeiffer WC, Lacerda LD, Malm O, Souza CMM, Silveria E, Batos WR (1989) Mercury concentrations in land waters of gold-mining areas in Rodonia. *Brazil. Science of the Total Environment* 87(88):233–240
- Porcella DB (1994) Mercury in the environment: biogeochemistry. In: Watras, C.J., Huckabee, J.W. (Editors.), *Mercury Pollution- Integration and Synthesis*. CRC Press, Boca Raton, FL, pp. 3–19.
- Pouilly M, Rejas D, Pérez T, Duprey JL, Molina CI, Hubas C, Guimarães JD (2013) Trophic Structure and Mercury Biomagnification in Tropical Fish Assemblages, Itenez River, Bolivia. *PLoS ONE* 8(5): e65054. <https://doi.org/10.1371/journal.pone.0065054> [Online May 31, 2013]
- R Core Team (2013) R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. URL <http://www.R-project.org/>.
- Reeves RR In: Smith BC, Crespo E, Notarbartolo Di Sciara G (editors) (2003) *Dolphins, whales and porpoises. 2002–2010 Conservation Action Plan for the World’s Cetaceans*. Gland, IUCN/SSC Cetacean Specialist Group: Switzerland, pp 139
- Rosas FCW, Lethi KK (1996) Nutritional and mercury content of milk of the Amazon river dolphin. *Inia geoffrensis*. *Comparative Biochemistry and Physiology* 115A(2):117–119
- Roulet M, Lucotte M, Canuel R, Rheault I, Tran S, De Freitas Gog YG, Farella N, Souza do Vale R, Amorim M (1998a) Distribution and partition of total mercury in waters of the Tapajos river basin, Brazilian Amazon. *Science of the Total Environment*. [https://doi.org/10.1016/S0048-9697\(98\)00093-x](https://doi.org/10.1016/S0048-9697(98)00093-x) [Online June 01, 1998]
- Roulet M, Lucotte M, Farella N, Serique G, Coelho H, Sousa Passos CJ, De Jesus da Silva E, Scavone de Andrade P, Mergler

- D, Amorim M (1998b) Effects of recent human colonisation on the presence of mercury in Amazonian ecosystems. *Water, Air and Soil Pollut* 112: 297–317; <https://doi.org/10.1023/a:1005073432015> [Online June 01, 1999]
- Roulet M, Lucotte M, Guimaraes JRD, Rheault I (2000) Methylmercury in the water, seston and epiphyton of an Amazonian river and floodplain, Tapajos River, Brazil. *Science of the Total Environment* 261: 43–59; [https://doi.org/10.1016/S0048-9697\(00\)00594-5](https://doi.org/10.1016/S0048-9697(00)00594-5) [Online October 16, 2000]
- Salinas C, Cubillos JC, Gómez R, Trujillo F, Caballero S (2013) Pig in a poke (gato por liebre): The “mota” (*Calophysus macropterus*) Fishery, Molecular Evidence of Commercialization in Colombia and Toxicological Analyses. *EcoHealth* 11(2):197–206; <https://doi.org/10.1007/s10393-013-0893-8> [Online January 14, 2014]
- Sarica S, Amyotb M, Harea L, Blanchfieldc P, Bodalyc RA, Hintelmann H, Lucotte M (2005) Mercury transfer from fish carcasses to scavengers in boreal lakes: the use of stable isotopes of mercury. *Environmental Pollution* 134:13–22; <https://doi.org/10.1016/j.envpol.2004.07.020> [Online March 14, 2005]
- Scheuhammer AM, Meyer MW, Sandheinrich MB, Murray MW (2007) Effects of environmental methylmercury on the health of wild birds, mammals, and fish. *Ambio* 36:12–18 [Online February 06, 2007]
- Shostell JM, Ruiz-García M (2010) An introduction to river dolphin species. New York: Nova Science Publishers Inc, pp 1–28
- Siciliano S, Emin-Lima NR, Costa AF, Rodrigues ALF, Magalhaes FA, Tosi CH, Garri RG, Silva CR, Silva JS (2008) Revisao do conhecimento sobre os mamíferos aquáticos da costa norte do Brasil. *Arquivos do Museu Nacional* 66:381–401
- Siebert U, Joiris C, Holcbeek L, Benke H, Faling K, Frese K, Petzinger E (1999) Potencial relation between mercury concentrations and necropsy findings in cetaceans from German waters of the North and Baltic Seas. *Marine Pollution Bulletin* 38: 285–295; [https://doi.org/10.1016/S0025-326X\(98\)00147-7](https://doi.org/10.1016/S0025-326X(98)00147-7) [Online April 15, 1999]
- Souza Araujo J, Giarrizzo T, Lima MO, Souza MB. (2016) Mercury and methyl mercury in fishes from Bacajá river (Brazilian Amazon): evidence for bioaccumulation and biomagnification. *Journal of Fish Biology* 89 (1): 249–263; <https://doi.org/10.1111/jfb.13027> [Online July 01, 2016]
- Trujillo, F (2000) Habitat use and social behaviour of the freshwater dolphin *Inia geoffrensis* (de Blainville 1817) in the Amazon and Orinoco basins. Ph.D. Thesis. Aberdeen University. Scotland. Pp 157
- Ullrich SM, Tanton TW, Abdrashitova SA (2001) Mercury in the aquatic environment: a review of factors affecting methylation. *Critical Reviews of Environmental Sciences and Technology* 31, 241–293. <https://doi.org/10.1080/20016491089226> [Online June 03, 2005]
- United Nations Environment Programme/Regional Ofce for Latin America and the Caribbean (UNEP/ROLAC) (2014) *The Minamata Convention on Mercury and its implementation in the Latin America and Caribbean region*, Uruguay: Montevideo
- Veiga M, Meech JA, Onate N (1994) Mercury pollution from deforestation. *Nature* 368: 816–817; <https://doi.org/10.1038/368816a0> [Online April 28, 1994]
- Veiga MM (1997) *Introducing new technologies for abatement of global mercury pollution in Latin America*, Rio de Janeiro, Brazil: UNIDO/UBC/CETEM/CNPq, pp 1–94
- Veiga MM, Hilton JJ, Lilly C (1999) Mercury in the Amazon: A comprehensive review with special emphasis on bioaccumulation and bioindicadores. Japan: Minamata, pp 19–39
- Venturieri R, Oliveira-da-Costa M, Gama C, Jaster CB (2017) Mercury Contamination within Protected Areas in the Brazilian Northern Amazon-Amapá State. *American Journal of Environmental Sciences* 13 (1): 11–21; <https://doi.org/10.3844/ajessp.2017.11.21> [Online November 21, 2018]
- Villas Bôas RC (1997) The mercury problem in the Amazon due to gold extraction. *Journal of Geochemical Exploration* 58:217–22. [https://doi.org/10.1016/S0375-6742\(96\)00075-1](https://doi.org/10.1016/S0375-6742(96)00075-1) [Online April 01, 1997]
- WCS (2017) Available: <http://aguasamazonicas.org/la-iniciativa/> [accessed October 21, 2018]
- Wei-Wei D, Ying X, Ding W, Yu-Jiang H (2006) Mercury concentrations in Yangtze Finless Porpoises (*Neophocaena phocaenoides asiaeorientalis*) from eastern Dongting Lake. *China. Fresenius Environmental Bulletin* 15(5):446–453
- Wren CD (1985) Probable case of mercury poisoning in a wild otter, *Lutra canadensis*, in northwestern Ontario. *Canada. Field-Naturalist* 99:112–114
- Wren CD (1986) A review of metal accumulation and toxicity in wild mammals: I. Mercury. *Environ. Res* 40: 210–244. [https://doi.org/10.1016/S0013-9351\(86\)80098-6](https://doi.org/10.1016/S0013-9351(86)80098-6) [Online June 01, 1986]
- Yang J (2001) Trace elements in Dall’s porpoise. *Phocoenoides dalli*, off the Sanriku coast of Japan, Department of Aquatic Bioscience, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo, 41–42
- Zhang HC, Zhou R, Zhou KY, Kamiya S (1996) The research of heavy metals in *Neophocaena phocaenoides* from Bohai Sea. *China Environmental Science* 16(2):107–112
- Zhou R, Zhou KY, Kamiya S (1993) Mercury levels in liver, kidney and muscle in *Neophocaena phocaenoides* from Yellow Sea. *Marine Environmental Science* 12(1):14–18