**MINI REVIEW**

# Using Crocodylians for monitoring mercury in the tropics

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## Abstract

Mercury contamination is a widespread phenomenon that impacts ecosystems worldwide. Artisanal Small Scale Gold Mining (ASGM) activities are responsible for more than a third of atmospheric Hg emission. Due to Hg toxicity and its broad and elevated prevalence in the environment resulting from ASGM activities in the tropics, its biomonitoring is essential to better understand the availability of its methylmercury (MeHg) form in the environment. The Minamata Convention was ratified with the objective to "*protect human health and the environment from anthropogenic emissions and releases of mercury compounds*". Biomagnification of MeHg occurs through the trophic food web, where it biomagnifies and bioaccumulates in top predators. To monitor environmental MeHg contamination, studies have evaluated the use of living organisms; however, reptiles are among the least documented vertebrates regarding MeHg exposure. In this review we evaluate the use of crocodylians for Hg biomonitoring in tropical ecosystems. We found that out of the 28 crocodiles species, only 10 have been evaluated regarding Hg contamination. The remaining challenges when using this taxon for Hg biomonitoring are inconsistencies in the applied methodology (e.g., wet versus dry weight, tissues used, quantification method). However, due to their life history traits, crocodylians are particularly relevant for monitoring MeHg contamination in regions where ASGM activities occur. In conclusion and given their ecological and socio-economic importance, crocodylians are at great risk of MeHg contamination and are excellent bioindicators for tropical ecosystems.

**Keywords** Bioindicator · Mercury · Tropical ecosystems · Blood · Keratinized tissues · Goldmining

## Introduction

Mercury (Hg) is one of the most concerning global contaminants (Chen et al. 2018) and its ecological processes in the Southern Hemisphere are only recently being described (Chen and Evers 2023). Mercury originates from both natural and anthropogenic sources, with artisanal and small-scale gold mining (ASGM) and fossil fuel combustion being the principal sources of its direct release into ecosystems (Mason et al. 1994, 2012; Obrist et al. 2018). Under anoxic conditions, inorganic Hg is methylated via sulfate-reducing microorganisms into methylmercury (MeHg), the most bioavailable and toxic form of Hg (Compeau and Bartha 1985; Benoit et al. 2003; Podar et al. 2015). MeHg bioaccumulates within organisms over time and biomagnifies through the

trophic web, where it may reach levels of concern as measured in different tissues of top predators (Lavoie et al. 2013; Eagles-Smith et al. 2018). The methylmercury form is extremely concerning due to its toxicity for human and wildlife. Deleterious effects attributed to MeHg contamination encompass (but are not limited to) immunotoxicity, alteration of neurological capacity and neuro-behavioral function, impairment of reproduction, and offspring quality (Cordier et al. 2002; Basu et al. 2005; Scheuhammer et al. 2007; Tan et al. 2009; Chin et al. 2013; Landler et al. 2017; Maqbool et al. 2017; Morcillo et al. 2017; Evers 2018).

Due to its toxicity and its capacity to bioaccumulate in living organisms, the evaluation of Hg, and in particular MeHg, concentrations in ecosystems is important to understand for regulatory and policy decisions regarding ecosystem and human health (Evers et al. 2016; Gustin et al. 2016). The Minamata convention was ratified with the objectives to "*protect human health and the environment from anthropogenic emissions and releases of mercury compounds*" (United Nations Environment Programme (2013)). To assess its effectiveness, the selection of appropriate bioindicators, such as those that are of high importance as resources for

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human consumption, and taxa that are at great risk of Hg exposure, are needed (Evers et al. 2016).

In this regard, studies have evaluated the use of living organisms to monitor environmental contamination, with particular attention given to vertebrates (Gómez-Ramírez et al. 2014; Di Marzio et al. 2018; De Paula Gutiérrez, Agudelo (2020); Haskins et al. 2021). The use of bioindicators offers several advantages over standard methods which analyze Hg in soil, sediment, and water. Mercury and MeHg can concentrate in tissues at varying levels, based on the type of tissue. Some including blood, brain, and keratin-based tissues facilitate analytical detection of total Hg as a high percentage of the Hg is in its methyl form (i.e., > 90%). Quantification of total Hg in key tissue types (e.g., those with a high percentage of MeHg) of targeted bioindicator species provides valuable information on MeHg availability in an ecosystem. While fish, birds, and mammals have been extensively used as bioindicators, reptiles have been more infrequently considered in ecotoxicological studies. Despite the increasing number of studies on snakes, turtles and crocodiles showing their capacities to be used as bioindicators species (Burger et al. 2005; Schneider et al. 2011; Lázaro et al. 2015; Lemaire et al. 2018; Haskins et al. 2021), reptilian model species remain underrepresented.

The tropics are particularly affected by Hg contamination, where ASGM represents the major source of emissions (United Nation Environment Programme (2019)). However, studies in tropical regions generally lag behind Northern Hemisphere regions (Carravieri et al. 2013; Albert et al. 2019, Diez et al. 2019, Chen and Evers 2023). Tropical ecosystems contain a high diversity of reptilians which, in regard to their natural history traits, makes them high quality candidates for biomonitoring MeHg contamination. Crocodylians, being top predators inhabiting tropical and sub-tropical ecosystems, have been used in multiple studies and prove to be excellent bioindicators of environmental Hg contamination (Schneider et al. 2015; Nilsen et al. 2017a; Lemaire et al. 2021a). In this review, we will examine the main findings, highlight the remaining challenges, and propose recommendations for using crocodylians to monitor environmental Hg contamination and to contribute to global biomonitoring efforts that will contribute toward the evaluation of the effectiveness of the 'Minamata Convention on Mercury'.

## Methods

A literature review was conducted on January 30th, 2023, using Scopus, Web of Science, and the Google Scholar database, with the keywords "Crocodylians", "Mercury", and "Methylmercury". To ensure the relevance of the studies, we excluded those that focused solely on mercury contamination in captive crocodiles and instead focused on studies on wild crocodylian populations. While this literature review may not have been exhaustive, it did provide a robust basis for a global comparison of Hg in various tissues of wild crocodylians from around the world.

## Results and Discussion

### Study species and locations

This review demonstrates that although Hg contamination has been documented in crocodylians for approximately 35 years, literature remains limited. In January 2023 only 39 studies reported Hg contamination in wild crocodylid populations, with a recent increase of publications in the last decade. Delany et al. (1988) were the first to publish Hg contamination in muscle tissue of 32 American alligators *Alligator mississippiensis* from various populations in Florida, USA. Since then, out of the 28 extant crocodylid species, Hg contamination has only been documented in 10 of them, accounting for 35,7% (Fig. 1). Among these, three species encompass most of the published studies with *A. mississippiensis* being the most studied species with 16 studies (41%), followed by eight studies (20%) on the Spectacled caiman (*Caiman crocodilus*), and six studies (15%) on the Black caiman (*Melanosuchus niger*) (Fig. 1). In contrast, the Chinese alligator (*Alligator sinensis*) and the Nile crocodile (*Crocodylus niloticus*) have each been the subject of one study (Fig. 1).

Crocodylians are widely distributed across tropical and subtropical ecosystems (Fig. 2). However, most studies on crocodylian Hg contamination have focused on the Americas, while Africa and Asia encompass only two studies where one examined Hg levels in the Chinese alligator (*A. sinensis*) in China, and another in the Nile crocodile (*C. niloticus*) Hg contamination in Zambia (Almli et al. 2005; Xu et al. 2006) (Fig. 2).

Among the investigated species, most of them are species of conservation concern based on the IUCN Red List for Endangered Species assessment, which stresses the need to extend Hg evaluation to all crocodylians to serve as large-scale bioindicators. Additionally, Hg contamination represents an already documented, deleterious impact in archosaurs (Wolfe et al. 1998; Scheuhammer et al. 2007; Ackerman et al. 2016). It has been demonstrated that in alligatorids, Hg contamination, even at low levels, negatively impacts physiological processes such as osmoregulation, hepatic function, and endocrine processes (Lemaire et al. 2021b), damages DNA of erythrocytes (Marrugo-Negrete et al. 2019), alters body condition (Nilsen et al. 2017a), and disrupts embryonic development (Lemaire et al. 2021c). Therefore, it is crucial to gain a better understanding of the
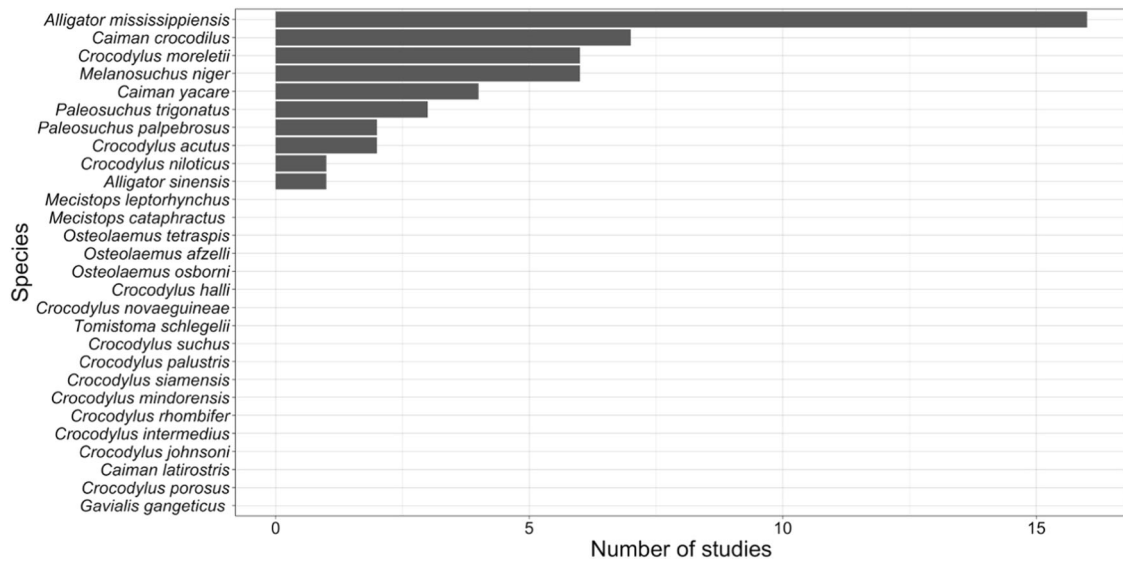
Fig. 1 Number of studies on Hg contamination in wild crocodylians which were published by January 30th, 2023
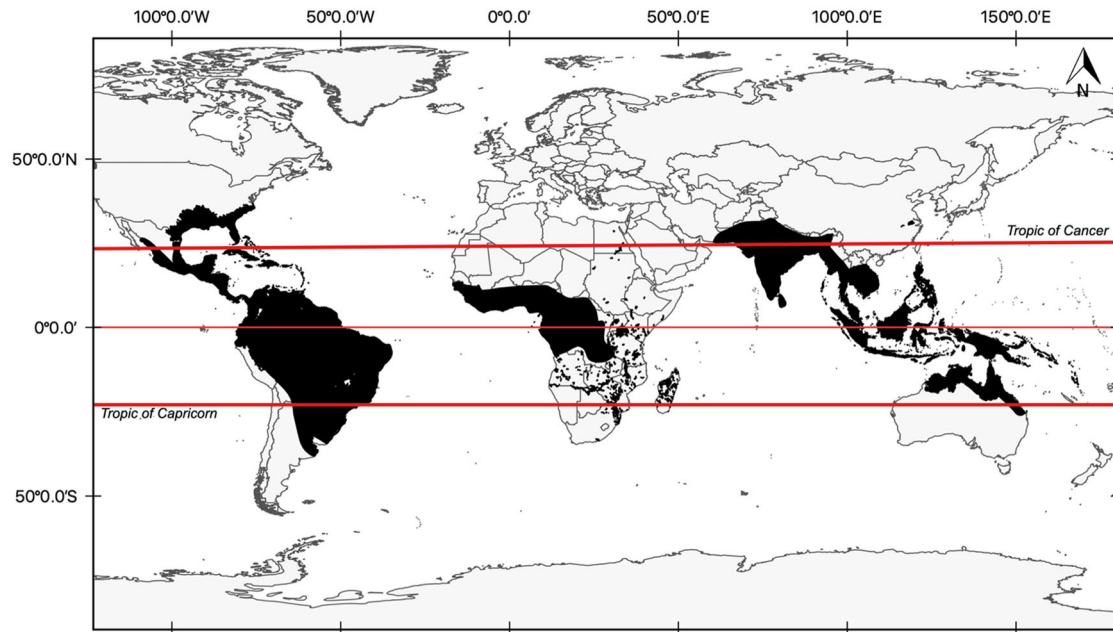


Fig. 2 Global distribution range of crocodylian species

threat that Hg contamination poses to crocodylians. The available literature emphasizes the urgent need to better understand its impact on this taxon.

## Mercury quantification

Studies show that in the 10 crocodylian species that have been investigated, Hg concentrations vary according to body size, habitat type, and geographic location. Such findings emphasize the need to better understand how different tissue types correlate with confounding morphometric and environmental factors. Detailed information on Hg concentrations measured in wild populations are summarized in Table 1.

A variety of tissues have been analyzed to investigate Hg contamination in crocodylians including blood, muscle, internal organs, and keratinized tissues (e.g., scutes). However, due to the limited literature available and the diversity of matrices studied, straightforward comparisons among studies and species is currently challenging. Moreover, the methodology for sample preparation varies among studies. A major challenge that hinders robust comparison

**Table 1** Total mercury concentration measured in different tissues of crocodylians, Mean ± SD/or SE [Min – Max] in µg.g$^{-1}$, body size Mean ± SD/or SE [Min – Max] in cm, year of collection and location, published between 1988 and January 2023.

| Species | Location | Year of collection | $n$ | Tissue | Body size | Hg concentration | Authors |
|---|---|---|---|---|---|---|---|
| American alligator (*Alligator mississippiensis*) | Florida, USA | 1985 | 24 | Muscle (ww) | 303 cm [290–380] | 0.61 [-] | Delany et al. 1988 |
| | Everglades, Florida, USA | 1992–1993 | 12 | Liver (ww) | - | 39.99 ± 24.05 [8.86–99.48] | Heaton-Jones et al. 1997 |
| | Florida, USA | 1992 | 12 | Liver (ww) | - | 2.53 ± 4.38 [0.14–16.01] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Kidneys (ww) | - | 25.85 ± 14.63 [5.37–65.53] | |
| | Florida, USA | 1992 | 12 | Kidneys (ww) | - | 1.58 ± 2.35 [0.15–9.56] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Spleen (ww) | - | 3.70 ± 3.28 [1.04–13.10] | |
| | Florida, USA | 1992 | 12 | Spleen | - | 0.45 ± 0.48 [0.09–1.31] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Tail muscle (ww) | - | 2.61 ± 0.91 [1.11–4.28] | |
| | Florida, USA | 1992 | 12 | Tail muscle (ww) | - | 0.33 ± 0.28 [0.04–1.00] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Leg muscle (ww) | - | 2.70 ± 1.41 [0.61–6.05] | |
| | Florida, USA | 1992 | 12 | Leg muscle (ww) | - | 0.28 ± 0.19 [0.05–0.60] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Heart (ww) | - | 2.31 ± 1.18 [1.21–4.62] | |
| | Florida, USA | 1992 | 12 | Heart (ww) | - | 0.30 ± 0.22 [0.08–0.85] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Brain (ww) | - | 1.37 ± 0.61 [0.52–2.50] | |
| | Florida, USA | 1992 | 12 | Brain (ww) | - | 0.16 ± 0.09 [0.03–0.31] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Spinal cord (ww) | - | 1.34 ± 0.57 [0.45–2.55] | |
| | Florida, USA | 1992 | 12 | Spinal cord (ww) | - | 0.97 ± 1.64 [0.06–4.98] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Ovaries (ww) | - | 0.70 ± 0.33 [0.39–1.34] | |
| | Florida, USA | 1992 | 12 | Ovaries (ww) | - | 1.30 ± 1.64 [0.03–5.91] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Oviducts (ww) | - | 1.19 ± 0.29 [0.89–1.59] | |
| | Florida, USA | 1992 | 12 | Oviducts (ww) | - | 1.20 ± 1.87 [0.06–5.42] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Testes (ww) | - | 1.17 ± 0.59 [0.31–2.35] | |
| | Florida, USA | 1992 | 12 | Testes (ww) | - | 0.19 ± 0.17 [0.01–0.48] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Tail scales (ww) | - | 1.03 ± 0.42 [0.40–1.86] | |
| | Florida, USA | 1992 | 12 | Tail scales (ww) | - | 0.34 ± 0.33 [0.04–1.10] | |

**Table 1** (continued)

| Species | Location | Year of collection | n | Tissue | Body size | Hg concentration | Authors |
|---|---|---|---|---|---|---|---|
| | Everglades, Florida, USA | 1992–1993 | 12 | Lungs (ww) | - | 0.98 ± 0.48 [0.39–1.76] | |
| | Florida, USA | 1992 | 12 | Lungs (ww) | - | 0.27 ± 0.20 [0.08–0.63] | |
| | Everglades, Florida, USA | 1992–1993 | 12 | Bile (ww) | - | 0.17 ± 0.12 [<0.01–0.53] | |
| | Florida, USA | 1992 | 12 | Bile (ww) | - | 0.23 ± 0.20 [0.03–0.59] | |
| | Everglades, Florida, USA | 1994 | 18 | Muscle (dw) | - | 5.57 ± 0.47 | Jagoe et al. 1998 |
| | Central Florida, USA | 1994 | 21 | Muscle (dw) | - | 1.85 ± 0.35 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Muscle (dw) | - | 0.80 ± 0.12 | |
| | Savannah River, South Carolina, USA | 1994 | 17 | Muscle (dw) | - | 4.83 ± 0.88 | |
| | Everglades, Florida, USA | 1994 | 18 | Liver (dw) | - | 41.03 ± 5.90 | |
| | Central Florida, USA | 1994 | 21 | Liver (dw) | - | 14.61 ± 3.19 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Liver (dw) | - | 4.30 ± 0.97 | |
| | Savannah River, South Carolina, USA | 1994 | 14 | Liver (dw) | - | 14.90 ± 2.24 | |
| | Everglades, Florida, USA | 1994 | 17 | Kidneys (dw) | - | 36.42 ± 53.23 | |
| | Central Florida, USA | 1994 | 21 | Kidneys (dw) | - | 12.59 ± 2.65 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Kidneys (dw) | - | 4.82 ± 1.34 | |
| | Everglades, Florida, USA | 1994 | 17 | Scutes (dw) | - | 5.83 ± 1.04 | |
| | Central Florida, USA | 1994 | 20 | Scutes (dw) | - | 0.52 ± 0.09 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Scutes (dw) | - | 0.29 ± 0.03 | |
| | Savannah River, South Carolina, USA | 1994 | 39 | Scutes (dw) | - | 5.14 ± 0.64 | |
| | Central Florida, USA | 1994 | 21 | Claws (dw) | - | 2.69 ± 0.56 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Claws (dw) | - | 1.67 ± 0.16 | |
| | Savannah River, South Carolina, USA | 1994 | 11 | Whole blood (dw) | - | 2.19 ± 0.38 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Bone (dw) | - | 0.16 ± 0.02 | |
| | Okefenokee, South Georgia, USA | 1994 | 8 | Fat (dw) | - | 0.19 ± 0.06 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Spleen (dw) | - | 0.63 ± 0.12 | |
| | Okefenokee, South Georgia, USA | 1994 | 9 | Brain (dw) | - | 0.46 ± 0.14 | |
| | WCA, Everglades, Florida, USA | 1994 | 10 | Kidneys (dw) | - | 35.00 ± 6.02 | Yanochko et al. 1997 |
| | WCA, Everglades, Florida, USA | 1994 | 10 | Tail scutes (dw) | - | 6.33 ± 1.04 | |

**Table 1** (continued)

| Species | Location | Year of collection | n | Tissue | Body size | Hg concentration | Authors |
|---|---|---|---|---|---|---|---|
| | WCA, Everglades, Florida, USA | 1994 | 10 | Liver (dw) | - | 42.15 ± 6.64 | |
| | WCA, Everglades, Florida, USA | 1994 | 10 | Muscle (dw) | - | 5.68 ± 0.75 | |
| | Holiday Park, Everglades, Florida, USA | 1994 | 7 | Kidneys (dw) | - | 38.46 ± 9.92 | |
| | Holiday Park, Everglades, Florida, USA | 1994 | 7 | Tail scutes (dw) | - | 5.12 ± 1.01 | |
| | Holiday Park, Everglades, Florida, USA | 1994 | 8 | Liver (dw) | - | 39.75 ± 10.01 | |
| | Holiday Park, Everglades, Florida, USA | 1994 | 8 | Muscle (dw) | - | 5.43 ± 0.53 | |
| | Par Pound, South Carolina, USA | 1994 | 39 | Tail scutes (dw) | - | 4.58 ± 0.63 | |
| | Par Pound, South Carolina, USA | 1994 | 17 | Liver (dw) | - | 17.73 ± 2.56 | |
| | Par Pound, South Carolina, USA | 1994 | 21 | Muscle (dw) | - | 4.08 ± 0.46 | |
| | South Louisiana, USA | 1998 | 42 | Muscle (ww) | [124–368] | 0.131 [0.047–0.386] | Elsey et al. 1999 |
| | Everglades, Florida, USA | 1999 | 28 | Liver (ww) | 77.4 ± 9.7 SVL [58.5–93.5] | 4.89 ± 3.99 [0.6–17] | Rumbold et al. 2002 |
| | Everglades, Florida, USA | 1999 | 28 | Tail muscle (ww) | 77.4 ± 9.7 SVL [58.5–93.5] | 0.64 ± 0.04 [0.1–1.8] | |
| | Caddo Lake, Texas / Louisiana, USA | 2007 | 2 | Muscle (dw) | 149 ± 55.2 | 0.795 ± 0.010 | Chumchal et al. 2011 |
| | Caddo Lake, Texas / Louisiana, USA | 2007 | 2 | Liver (dw) | 149 ± 55.2 | 2.263 ± 0.289 | |
| | South Carolina, USA | 2008 | 33 | Liver (ww) | 234.4 ± 9.2 [152–336] | 5.68 ± 1.4 | Campbell et al. 2010 |
| | Florida, USA | 2009–2010 | 62 | Liver (dw) | [66.5–370] | [0.0522–23.9] | Horai et al. 2014 |
| | Florida, USA | 2012 | 37 | Whole blood (ww) | [43.9–153.5] SVL | 0.1937 [0.0567–1.380] | Nilsen et al. 2017b |
| | Florida, USA | 2012 | 37 | Muscle (ww) | [43.9–153.5] SVL | 0.2431 [0.0453–1.183] | |
| | Florida, USA | 2012 | 37 | Liver (ww) | [43.9–153.5] SVL | 3.5941 [0.5668–14.293] | |
| | Florida, USA | 2012 | 30 | Scutes (ww) | [43.9–153.5] SVL | 0.3185 [0.0622–1.9659] | |
| | Merritt Island, Florida, USA | 2007–2014 | 174 | Whole blood (ww) | [87–187.2] SVL | 0.152 [0.0358–1.0664] | Nilsen et al. 2017a |
| | Yawkey, South Carolina, USA | 2011–2014 | 15 | Whole blood (ww) | 136 ± 21 SVL [112–183] | 0.150 ± 0.049 [0.048–0.238] | Nilsen et al. 2019 |
| | Bear Island, South Carolina, USA | 2011–2014 | 14 | Whole blood (ww) | 119 ± 22 SVL [80–165] | 0.118 ± 0.058 [0.044–0.234] | |
| | Kissimmee, Florida, USA | 2011–2014 | 12 | Whole blood (ww) | 129 ± 33 SVL [90–178] | 0.393 ± 0.204 [0.185–0.796] | |

**Table 1** (continued)

| Species | Location | Year of collection | n | Tissue | Body size | Hg concentration | Authors |
|---|---|---|---|---|---|---|---|
| | Lochloosa, Florida, USA | 2011–2014 | 10 | Whole blood (ww) | 126 ± 31 SVL [94–180] | 0.146 ± 0.067 [0.039–0.251] | |
| | St. Johns, Florida, USA | 2011–2014 | 11 | Whole blood (ww) | 136 ± 20 SVL [96–168] | 0.153 ± 0.049 [0.079–0.234] | |
| | Trafford, Florida, USA | 2011–2014 | 12 | Whole blood (ww) | 121 ± 25 SVL [90–154] | 0.194 ± 0.073 [0.067–0.359] | |
| | Everglades, Florida, USA | 2011–2014 | 14 | Whole blood (ww) | 110 ± 23 SVL [92–157] | 1.364 ± 0.673 [0.438–2.765] | |
| | Cape Fear River North Carolina, USA | 2021 | 13 | Blood (ww) | 94.7 ± 37.2 SVL [50.4–190.8] | 0.0792 ± 0.0796 [0.0216–0.3355] | Belcher et al. 2022 |
| | Lake Waccamaw, North Carolina, USA | 2021 | 31 | Blood (ww) | 95.4 ± 27.5 SVL [57.6–148.9] | 0.5111 ± 0.2461 [0.1522–0.9459] | |
| | St. Johns River, Florida, USA | 2021 | 24 | Blood (ww) | 119.1 ± 31.9 SVL [50.9–163.1] | 0.1483 ± 0.0489 [0.0544–0.2443] | |
| | Florida, USA | - | 30 | Fat (ww) | - | 0.0482 ± 0.0137 | Burger et al. 2000 |
| | Florida, USA | - | 31 | Liver (ww) | - | 0.403 ± 0.0801 | |
| | Florida, USA | - | 30 | Abdominal muscle (ww) | - | 0.0756 ± 0.016 | |
| | Florida, USA | - | 29 | Skin (ww) | - | 0.0558 ± 0.0129 | |
| | Florida, USA | - | 29 | Tail muscle (ww) | - | 0.0625 ± 0.0165 | |
| | Florida, USA | - | 22 | Tail tip (ww) | - | 0.0514 ± 0.00869 | |
| | Savannah River, South Carolina, USA | 2020–2021 | 31 | Tail muscle (ww) | - | 1.31 ± 0.18 [0.077 -4.33] | Kojima et al. 2023 |
| | Savannah River, South Carolina, USA | 2020–2021 | 53 | Whole blood (ww) | - | 0.938 ± 0.10 [0.076–3.41] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 26 | Brain (dw) | 73.13 ± 4.43 SVL | 0.270 ± 0.043 [0.072–1.143] | Moore et al. 2022 |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Claws (dw) | 73.13 ± 4.43 SVL | 0.759 ± 0.130 [0.055–3.789] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Front leg muscle (dw) | 73.13 ± 4.43 SVL | 0.388 ± 0.067 [0.113–1.827] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Liver (dw) | 73.13 ± 4.43 SVL | 3.120 ± 0.760 [0.291–16.87] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Gonad (dw) | 73.13 ± 4.43 SVL | 0.247 ± 0.056 [0.030–1.525] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Heart (dw) | 73.13 ± 4.43 SVL | 0.465 ± 0.088 [0.133–2.458] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Jaw muscle (dw) | 73.13 ± 4.43 SVL | 0.588 ± 0.109 [0.169–3.030] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Kidney (dw) | 73.13 ± 4.43 SVL | 3.183 ± 0.689 [0.488–16.101] | |
| | | 2002 | 27 | | | | |

**Table 1** (continued)

| Species | Location | Year of collection | n | Tissue | Body size | Hg concentration | Authors |
|---|---|---|---|---|---|---|---|
| | Rockefeller Wildlife Refuge, Louisiana, USA | | | Rear leg muscle (dw) | 73.13 ± 4.43 SVL | 0.425 ± 0.080 [0.128–2.204] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Dermal tail scutes (dw) | 73.13 ± 4.43 SVL | 0.523 ± 0.210 [0.032–5.789] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Tail muscle (dw) | 73.13 ± 4.43 SVL | 0.478 ± 0.090 [0.154–2.455] | |
| | Rockefeller Wildlife Refuge, Louisiana, USA | 2002 | 27 | Blood (ww) | 73.13 ± 4.43 SVL | 0.122 ± 0.022 [0.029–0.532] | |
| Chinese Alligator (*Alligator sinensis*) | Changwing Nature Reserve, China | 2004 | 2 | Heart (dw) | - | 0.347 [0.343–0.350] | Xu et al. 2006 |
| | Changwing Nature Reserve, China | 2004 | 2 | Lung (dw) | - | 0.327 [0.248–0.405] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Liver (dw) | - | 0.559 [0.492–0.626] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Stomach (dw) | - | 0.291 [0.232–0.349] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Kidneys (dw) | - | 0.902 [0.869–0.935] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Intestine (dw) | - | 0.399 [0.389–0.409] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Tracheas (dw) | - | 0.120 [0.092–0.147] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Pancreas (dw) | - | 0.061 [0.042–0.080] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Reproductive organs (dw) | - | 0.059 [0.032–0.085] | |
| | Changwing Nature Reserve, China | 2004 | 2 | Muscle (dw) | - | 0.193 [0.105–0.281] | |
| Spectacled Caiman (*Caiman crocodilus*) | Rio Purus, Brazil | 2008 | 10 | Muscle (ww) | 75.4 ± 12 SVL [62–98] | 0.2912 ± 0.2128 [0.0632–0.6806] | Schneider et al. 2012 |
| | Rio Purus, Brazil | 2008 | 7 | Muscle (dw) | 75 ± 10 SVL [66–94] | 0.234 ± 0.144 [0.132–0.447] | Schneider et al. 2015 |
| | Rio Purus, Brazil | 2008 | 7 | Epidermal scale (dw) | 75 ± 10 SVL [66–94] | 3.350 ± 2.143 [0.500–7.150] | |
| | Rio Purus, Brazil | 2008 | 7 | Bone (dw) | 75 ± 10 SVL [66–94] | 0.153 ± 0.121 [0.040–0.370] | |
| | La Mojana, Colombia | 2016 | 45 | Blood (ww) | [50–80] TL | 0.039 ± 0.030 | Marrugo-Negrete et al. 2019 |
| | La Mojana, Colombia | 2016 | 45 | Claws (ww) | [50–80] TL | 0.647 ± 0.547 | |
| | La Mojana, Colombia | 2016 | 45 | Scutes (ww) | [50–80] TL | 0.366 ± 0.205 | |
| | La Mojana, Colombia | 2016 | 20 | Blood (ww) | [50–80] TL | 0.008 ± 0.003 | |
| | La Mojana, Colombia | 2016 | 20 | Claws (ww) | [50–80] TL | 0.131 ± 0.038 | |
| | La Mojana, Colombia | 2016 | 20 | Scutes (ww) | [50–80] TL | 0.032 ± 0.006 | |
| | French Guiana | 2016–2020 | 48 | Claws (dw) | 66.60 ± 24.11 TL [31.0–176.0] | 2.692 ± 1.608 [0.321–8.807] | Lemaire et al. 2021d |
| | French Guiana | 2016–2020 | 47 | Scutes (dw) | 66.60 ± 24.11 TL [31.0–176.0] | 2.638 ± 1.497 [0.307–7.407] | |

**Table 1** (continued)

| Species | Location | Year of collection | n | Tissue | Body size | Hg concentration | Authors |
|---|---|---|---|---|---|---|---|
| | French Guiana | 2016–2020 | 26 | Red Blood Cells (dw) | 66.60 ± 24.11 TL [31.0–176.0] | 0.963 ± 0.612 [0.145–2.244] | |
| | French Guiana | 2016–2020 | 40 | Whole blood (dw) | 66.60 ± 24.11 TL [31.0–176.0] | 0.605 ± 0.380 [0.089–1.532] | |
| | French Guiana | 2019–2020 | 21 | Whole blood (dw) | 35.9 ± 7.7 SVL [20.2–48.5] | 0.676 ± 0.414 [0.168–1.532] | Lemaire et al. 2021b |
| | Rio Purus, Brazil | - | 8 | Muscle (ww) | 90 ± 14 [62–105] | 0.362 ± 0.231 [0.114–0.834] | Eggins et al. 2015 |
| | | | 15 | Liver (ww) | 90 ± 14 [62–105] | 1.701 ± 1.249 [0.035–5.305] | |
| | | | 11 | Blood (ww) | 90 ± 14 [62–105] | 0.060 ± 0.063 [0.020–0.240] | |
| | | | 8 | Keratin (ww) | 90 ± 14 [62–105] | 3.527 ± 3.095 [0.576–10.172] | |
| | French Guiana | - | 34 | Whole blood (dw) | 72.3 ± 24.7 TL [40.6–176.0] | 0.61 ± 0.39 [0.09–1.53] | Lemaire et al. 2022 |
| Yacaré (*Caiman yacare*) | La Paz, Bolivia | 2007–2008 | 64 | Muscle (ww) | < 180 TL | 0.21 ± 0.22 | Rivera et al. 2016 |
| | Colorado-Maja lakes, Bolivia | 2017 | 7 | Fat (ww) | [177–220] | 0.025 ± 0.03 | Salazar-Pammo et al. 2021 |
| | Colorado-Maja lakes, Bolivia | 2017 | 7 | Muscle (ww) | [177–220] | 0.15 ± 0.06 | |
| | Colorado-Maja lakes, Bolivia | 2017 | 7 | Kidneys (ww) | [177–220] | 0.57 ± 0.30 | |
| | Colorado-Maja lakes, Bolivia | 2017 | 7 | Liver (ww) | [177–220] | 1.81 ± 0.80 | |
| | Paraguay River, Pantanal, Brazil | - | 17 | Caudal scutes (ww) | - | 0.0957 ± 0.0922 | Lázaro et al. 2015 |
| | Bentos Gomes River, Pantanal, Brazil | - | 22 | Caudal scutes (ww) | - | 0.2639 ± 0.1587 | |
| | Paraguay River, Pantanal, Brazil | - | 17 | Claws (ww) | - | 0.8455 ± 0.6227 | |
| | Bentos Gomes River, Pantanal, Brazil | - | 22 | Claws (ww) | - | 1.9447 ± 0.7037 | |
| | Pantanal, Brazil | - | 79 | Tail muscle (ww) | - | [0.02–0.36] | Vieira et al. 2011 |
| American Crocodile (*Crocodylus acutus*) | Rio Grande Tárcoles, Costa Rica | 2003 | 6 | Scutes (ww) | 155.7 ± 5.5 SVL [134–172] | 0.0935 ± 0.027 | Rainwater et al. 2007 |
| | Belize | 2019–2019 | 30 | Scutes mix (dw) | - | [0.002–7.33] | Thirion et al. 2022 |
| Morelet's Crocodile (*Crocodylus moreletii*) | Gold Button Lagoon, Belize | 1997–2001 | 9 | Scutes (ww) | 89.8 ± 6.7 SVL [65.0–129.5] | 0.0987 ± 0.0216 | Rainwater et al. 2007 |
| | New River Watershed, Belize | 1997–2001 | 10 | Scutes (ww) | 104.4 ± 9.6 SVL [59.5–156.7] | 0.0727 ± 0.0204 | |
| | Campeche State, Mexico | 2012 | 92 | Scutes (dw) | 145.6 ± 37.5 SVL [75–288] | 5.4 ± 8.3 | Trillanes et al. 2014 |
| | Rio Hondo, Mexico | 2012–2013 | 20 | Scutes (ww) | [32–190.5] | 0.3741 ± 0.4294 | Buenfil-Rojas et al. 2015 |
| | Mexico | 2016–2018 | 5 | Claws (ww) | - | 1.31 ± 0.32 | Buenfil-Rojas et al. 2020 |

**Table 1** (continued)

| Species | Location | Year of collection | n | Tissue | Body size | Hg concentration | Authors |
|---|---|---|---|---|---|---|---|
| | Mexico | 2016–2018 | 50 | Scutes (ww) | - | 0.27 ± 0.28 | |
| | Mexico | 2016–2018 | 47 | Erythrocytes (ww) | - | 0.16 ± 0.20 | |
| | Belize | 2016–2019 | 63 | Scutes mix (dw) | - | [0.002–1.73] | Thirion et al. 2022 |
| Nile Crocodile (*Crocodylus niloticus*) | Kafue River, Zambia | 1998 | 4 | Liver (ww) | [2.7–3.4] | 3.5 [0.97–20] | Almli et al. 2005 |
| | Luangwa, Zambia | 1998 | 5 | Liver (ww) | [2.0–4.0] | 3.7 [2.2–16] | |
| | Kafue River, Zambia | 1998 | 4 | Kidney (ww) | [2.7–3.4] | 0.76 [0.60–15] | |
| | Luangwa, Zambia | 1998 | 5 | Kidney (ww) | [2.0– 4.0] | 2.7 [1.3–8.7] | |
| Black caiman (*Melanosuchus niger*) | Rio Purus, Brazil | 2008 | 13 | Muscle (dw) | 106 ± 28 SVL [87–191] | 0.177 ± 0.102 [0.056–0.371] | Schneider et al. 2015 |
| | Rio Purus, Brazil | 2008 | 13 | Epidermal scale (dw) | 106 ± 28 SVL [87–191] | 3.846 ± 2.815 [1.100–10.400] | |
| | Rio Purus, Brazil | 2008 | 11 | Bone (dw) | 106 ± 28 SVL [87–191] | 0.080 ± 0.093 [0.020–0.380] | |
| | Rio Purus, Brazil | 2008 | 11 | Muscle (ww) | 107.5 ± 31.44 SVL [75.3–190.9] | 0.1939 ± 0.0962 [0.0694–0.4066] | Schneider et al. 2012 |
| | Kaw-Roura Nature Reserve, French Guiana | 2013–2015 | 72 | Whole blood (dw) | 143.2 ± 61.3 TL [46.0–326.0] | 1.284 ± 0.672 [0.30–3.41] | Lemaire et al. 2021a |
| | Mamirauá Reservoir, Brazil | - | 60 | Muscle (ww) | [107–309] | 0.407 ± 0.114 [0.251–0.784] | Correira et al. (2014) |
| | Rio Purus, Brazil | - | 11 | Muscle (ww) | 102 ± 27 [75–191] | 0.176 ± 0.097 [0.057–0.371] | Eggins et al. 2015 |
| | Rio Purus, Brazil | - | 11 | Liver (ww) | 102 ± 27 [75–191] | 2.362 ± 2.257 [0.670–7.520] | |
| | Rio Purus, Brazil | - | 12 | Blood (ww) | 102 ± 27 [75–191] | 0.048 ± 0.032 [0.016–0.134] | |
| | Rio Purus, Brazil | - | 13 | Keratin (ww) | 102 ± 27 [75–191] | 2.092 ± 1.052 [0.209–4.029] | |
| | French Guiana | - | 25 | Whole blood (dw) | 176.4 ± 72.2 TL [71.0–326] | 1.56 ± 0.65 [0.54–2.89] | Lemaire et al. 2022 |
| Dwarf Caiman (*Paleosuchus palpebrosus*) | French Guiana | 2016–2020 | 13 | Claws (dw) | 79.42 ± 33.22 TL [34.2–150] | 8.351 ± 4.965 [2.028–20.042] | Lemaire et al. 2021d |
| | French Guiana | 2016–2020 | 13 | Scutes (dw) | 79.42 ± 33.22 TL [34.2–150] | 7.647 ± 4.742 [0.789–15.628] | |
| | French Guiana | 2016–2020 | 6 | Red Blood cells (dw) | 79.42 ± 33.22 TL [34.2–150] | 2.364 ± 1.884 [0.447–5.775] | |
| | French Guiana | 2016–2020 | 7 | Whole blood (dw) | 79.42 ± 33.22 TL [34.2–150] | 1.376 ± 0.986 [0.540–3.415] | |
| | French Guiana | - | 5 | Whole blood (dw) | 75.3 ± 44.6 TL [35.5–150] | 1.50 ± 1.18 [0.147–7.509] | Lemaire et al. 2022 |
| Smooth-fronted caiman (*Paleosuchus trigonatus*) | French Guiana | 2016–2020 | 50 | Claws (dw) | 62.11 ± 36.42 TL [22.8–143] | 2.420 ± 1.905 [0.147–7.509] | Lemaire et al. 2021d |
| | French Guiana | 2016–2020 | 48 | Scutes (dw) | 62.11 ± 36.42 TL [22.8–143] | 3.332 ± 3.066 [0.087–9.859] | |

**Table 1** (continued)

| Species | Location | Year of collection | *n* | Tissue | Body size | Hg concentration | Authors |
|---------|----------|--------------------|-----|--------|-----------|------------------|---------|
| | French Guiana | 2016–2020 | 11 | Red Blood Cells (dw) | 62.11 ± 36.42 TL [22.8–143] | 0.447 ± 0.270 [0.049–0.774] | |
| | French Guiana | 2016–2020 | 24 | Whole blood (dw) | 62.11 ± 36.42 TL [22.8–143] | 0.300 ± 0.178 [0.032–0.738] | |
| | French Guiana | 2017–2020 | 38 | Claws (dw) | [23.0–26.5] TL | [0.171–0.663] | Lemaire et al. 2021c |
| | French Guiana | 2017–2020 | 38 | Scutes (dw) | [23.0–26.5] TL | [0.092–0.251] | |
| | French Guiana | - | 20 | Whole blood (dw) | 82.8 ± 32.7 TL [27–143] | 0.35 ± 0.15 [0.10–0.70] | Lemaire et al. 2022 |

*ww* wet weight, *dw* dry weight.

across species, tissues, and locations is the methodology of Hg quantification, which can be reported in wet or dry tissue weight. Several studies have demonstrated that moisture content in crocodylian tissues varies greatly among species and locations, and can affect the interpretation of findings. Therefore, dry weight analysis appears to be essential for inter- and intraspecific comparison (Yanochko et al. 1997; Jagoe et al. 1998; Lemaire et al. 2021d).

Crocodylians are often a source of bushmeat for local communities and the consumption of their meat has been found to pose a health risk due to high Hg levels. Studies have focused on muscle tissue of crocodylians, which showed Hg concentrations as high as 4.28 µg.g$^{-1}$ (ww) in muscles of *A. mississippiensis* (Heaton-Jones et al. 1997), exceeding the WHO recommendation limit of 0.5 µg.g$^{-1}$ for safe consumption (WHO, World Health Organization (2011)).

Monitoring programs are needed to assess the risks associated with crocodylian meat consumption (Elsey et al. 1999; Vieira et al. 2011; Kojima et al. 2023), especially since muscle tissue contains over 70% of the methyl form (Vieira et al. 2011). However, the risk of Hg poisoning is strongly linked to intake frequency (Chételat et al. 2020). The liver plays a crucial role in detoxifying Hg and as a result, MeHg represents less than 40% of total Hg (THg) in liver tissues (Vieira et al. 2011). Analysis of total Hg is a cost-effective way of assessing MeHg levels in muscle tissue. While the MeHg concentration ratio in blood and keratinized tissues has been studied in other species, it has not been measured in crocodylians. Nevertheless, blood and keratinized tissues can serve as a proxy for concentrations of the methyl form with over 80% of total Hg found as MeHg (Oliveira Ribeiro et al. 1999; Renedo et al. 2017; Chételat et al. 2020). This approach can be useful in terms of analytical efficiency (time and costs).

Crocodylian tissues Hg concentrations are not confounded by sex of the individual (e.g., Elsey et al. 1999; Vieira et al. 2011; Lemaire et al. 2021a). While maternal

transfer has been shown in some crocodylian species such as *A. mississippiensis* (Nilsen et al. 2020) and *P. trigonatus* (Lemaire et al. 2021c), this phenomenon does not seem to affect Hg concentration in the blood of the females. Therefore, the entire population can be used for monitoring, regardless of sex, which is often difficult to determine in the field. This further facilitates harmonized comparison between studies.

To minimize impact on individuals, less-invasive sampling methods are preferred. Blood, and keratin tissues such as claws and scutes, are obtained via non-lethal sampling methods and provide information on the availability of MeHg in the environment. These tissues are known to be good predictors of Hg concentrations for internal tissues, such as liver and muscle (Jagoe et al. 1998; Burger et al. 2000). This is particularly important given the conservation status of most crocodylid species.

Clipping tail scutes is a commonly used sampling methods for crocodiles, as it further serves for individual identification and can be used for stable isotopes, DNA, and contaminant analysis (De Thoisy et al. 2006; Rainwater et al. 2007; Machkour-M'Rabet et al. 2009; Radloff et al. 2012; Trillanes et al. 2014; Pacheco-Sierra et al. 2016; Santos et al. 2018). Scutes and claws are keratin-rich excretion tissues that display high Hg concentrations due to strong affinity of Hg to sulfhydryl-groups contained in keratin (Alibardi 2003; Alibardi and Toni 2007). Mercury levels in keratinized tissues are considered to reflect long term contamination of the individual (Lázaro et al. 2015; Schneider et al. 2015; Marrugo-Negrete et al. 2019; Lemaire et al. 2021d). However, throughout the multiple studies which have been using scutes, only the studies from Schneider et al. (2015) and Lemaire et al. (2021d) give detailed information on the actual part of the scute that had been used for analysis. The importance of specification of the analyzed tissues was demonstrated in the study from Lemaire et al. (2021d): The authors compared Hg concentration when the total scute was analyzed to only the keratin layer of the scute, and show that bone inclusion lead

**Table 2** Mean of total mercury concentrations ± Standard Deviation measured in scutes of crocodylians ($\mu g.g^{-1}$ dry weight), compiled from the available literature, per species.

| Species | Mean Hg concentration ($\mu g.g^{-1}$) | References |
|---|---|---|
| **Dwarf caiman** (*Paleosuchus palpebrosus*) | 7.647 ± 4.742 | Lemaire et al. 2021d |
| **American alligator** (*Alligator mississippiensis*) | 4.069 ± 2.973 | Heaton-Jones et al. 1997; Yanochko et al. 1997; Jagoe et al. 1998; Burger et al. 2000; Nilsen et al. 2017b; Moore et al. 2022 |
| **Black caiman** (*Melanosuchus niger*) | 3.701 ± 0.205 | Schneider et al. 2015; Eggins et al. 2015 |
| **Smooth-fronted caiman** (*Paleosuchus trigonatus*) | 3.332 ± 3.066 | Lemaire et al. 2021d |
| **Spectacled caiman** (*Caiman crocodilus*) | 1.661 ± 1.582 | Schneider et al. 2015; Eggins et al. 2015; Marrugo-Negrete et al. 2019; Lemaire et al. 2021d |
| **Morelet's crocodile** (*Crocodylus moreletii*) | 1.407 ± 2.246 | Rainwater et al. 2007; Trillanes et al. 2014; Buenfil-Rojas et al. 2015; Buenfil-Rojas et al. 2020 |
| **Yacaré** (*Caiman yacare*) | 0.297 ± 0.196 | Lázaro et al. 2015 |
| **American crocodiles** (*Crocodylus acutus*) | 0.188 ± 0.005 | Rainwater et al. 2007 |

Conversion rate from original data in wet weight to dry weight were calculated from the moisture content available for scutes for each species (Yanochko et al. 1997; Lemaire et al. 2021d)

to an underrepresentation of Hg quantification (in the evaluation of the actual environmental contamination status). This highlights the importance of using only the keratin layer for analysis as proxy of long-term contamination.

In contrast, blood is another valuable tissue for biomonitoring studies, as it is involved in MeHg transportation to organs and reflects recent MeHg uptake directly related to the individual's diet (Lemaire et al. 2022; Manrico et al. 2017). In this order, ontogenetic dietary shift between juveniles and adults greatly influences measured total Hg concentration in blood, leading to a high variability in the relation between size and MeHg concentration. This ontogenetic shift explains why the relationship between blood Hg and body size is variable and was found in some studies (Eggins et al. 2015; Buenfil-Rojas et al. 2018; Lemaire et al. 2021a), but not in others (Yanochko et al. 1997; Eggins et al. 2015; Lawson et al. 2020). Therefore, when comparing Hg concentrations between different geographic areas, it is important to consider size of individuals. This emphasizes that keratinized tissues and blood are complementary in Hg biomonitoring studies as they reflect long-term and short-term contamination, respectively.

## Pattern of Hg concentrations

Among the available literature, scutes have been the most studied tissue in regard to species diversity. Eight crocodylian species from North and South America have been investigated, with mean Hg concentrations in scutes ranging from 0.188 to 7.647 $\mu g.g^{-1}$ dw (Table 2).

*P. palpebrosus* showed the highest Hg concentrations in scutes, followed by *A. mississippiensis*, *M. niger* and *P. trigonatus* (all > 3.3 $\mu g.g^{-1}$ dw, Table 2). In contrast, *C. acutus* showed the lowest Hg concentration with 0.188 $\mu g.g^{-1}$ dw.

The difference in Hg concentrations between species can be explained by their trophic ecology. As for other taxa, one of the sources of variation in Hg concentration in crocodylians is related to their trophic ecology (e.g., trophic position and foraging habitat, Lemaire et al. 2022). Additionally, geographic location plays a predominant role in Hg concentrations, depending on geological background and pollutant activities (Siqueira et al. 2018).

Among the four most contaminated crocodylian species, three are from the Amazon, a region known to present high geological Hg background, often enhanced by mining activities (United Nation Environment Programme (2019); Crespo-Lopez et al. 2023), factors known to increase Hg in trophic food webs. Crocodylian species from the Guiana Shield have the highest reported mean Hg concentrations so far, which is not surprising regarding the Hg-rich geological background and gold mining activities in the region (Rahm et al. 2015; Kroonenberg et al. 2022).

*A. mississippiensis* is the species with the second highest Hg concentration, which can be explained by the habitats where data were collected: *A. mississippiensis* lives in North America and is often encountered in close vicinity of anthropized areas (Beal and Rosenblatt 2020). Further, the species is found in the Florida Everglades, an ecosystem known to have high Hg concentrations (Janssen et al. 2022).

Some crocodylian species seem more likely to be contaminated with Hg depending on their geographical range and their trophic ecology, in this order, it would be of great importance to assess Hg geological background, trophic position and foraging ecology when monitoring Hg contamination to better understand the pattern of Hg concentrations in crocodylians.

## Crocodylians to monitor mercury contamination in the tropics

Due to their unique life history traits, crocodylians (alligators, caimans, true crocodiles, and gharials) are excellent indicators of MeHg contamination. They are high trophic-level predators living in aquatic ecosystems (Somaweera et al. 2020) which favors MeHg contamination due to biomagnification; they are long-lived animals (up to several decades) with a low metabolic, and a high tissue conversion rate (Garnett 1986; Webb et al. 1991) which favors MeHg bioaccumulation; they are territorial and sedentary (e.g., Hutton 1989; Fujisaki et al. 2014; Caut et al. 2019), which allows for precise spatial biomonitoring of MeHg contamination. Due to their large body size and robustness, sample collection is relatively straightforward. Additionally, the distribution of crocodylians across tropical and subtropical ecosystems is vast (Martin 2008), making them excellent candidates for large-scale monitoring. Overall, crocodiles represent a valuable tool in assessing the extent of MeHg availability in aquatic ecosystems.

Artisanal small-scale gold mining (ASGM) activities are among the main sources of Hg contributions to ecosystems, particularly in tropical and subtropical regions such as South America, Africa, and South-East Asia. The estimated annual release of Hg from ASGM activities exceeds 2000 tons each year (United Nation Environment Programme (2019)), with ASGM being responsible for up to 80% of local Hg emissions in Sub-Saharan Africa and 70% in South America (United Nation Environment Programme (2019)). Together, these two regions represent 70% of total Hg emission related to ASGM worldwide (United Nation Environment Programme (2019)). Unfortunately, there is a lack of biotic Hg data for many countries where ASGM activities are widely used (Kom et al. 1998; Peplow and Augustine 2014; Markham and Sangermano 2018, United Nation Environment Programme (2019)). Given the geographic range of ASGM activities, finding a suitable bioindicator to monitor Hg contamination is challenging. Crocodylians are an ideal candidate for several reasons, including a manageable number of species, their life history traits, and the potential to represent a broad contamination gradient.

Monitoring Hg contamination in crocodylians can help to assess the effectiveness of global biomonitoring. While reptiles are not listed as focal taxa within the Minamata Convention (Evers et al. 2016), there is still tremendous value in understanding MeHg availability to crocodylians and the potential adverse impacts on their behavior, physiology and reproductive success. Sample collection from crocodylians is (relatively) straightforward as there are sufficient tissues (e.g., blood and scutes) that can be sampled non-lethally to monitor Hg contamination over different time scales (see 'Methods'), including retrospective Hg analysis via museum specimens. Using crocodylians as bioindicators can help us to understand the extent and impact of Hg contamination from ASGM activities, and to work towards understanding its harmful effects on both wildlife and human populations, even more in areas where geological Hg is naturally high (e.g., Guyana Shield).

## Recommendations

The present review highlights several biases that limit comparisons among studies, species, and tissues in the assessment of Hg contamination in crocodylians. One of these biases is the quantification of Hg concentrations in wet- or dry weight, which can be tissue-specific and the variability among individuals and location as shown in *A. mississippiensis* (Yanochko et al. 1997; Jagoe et al. 1998), *P. palpebrosus*, *C. crocodilus*, and *P. trigonatus* (Lemaire et al. 2021d). To enable rigorous comparison of Hg contamination among species and locations, the use of dry samples should be emphasized.

The use of keratinized tissues such as scutes provides valuable information on long-term Hg contamination of an individual via a minimally invasive method. While this tissue has been used in many studies, the actual part of the scute used during analytical procedure is not yet standardized. Scutes are used as keratinized tissues to study the long-term accumulation of Hg. However, as first highlighted by Schneider et al. (2015) and then demonstrated by Lemaire et al. (2021d), using full scutes results in variation of measured Hg concentrations due to the integration of unknown quantities of bone and connective tissues. To avoid this bias, only the keratin layer should be used when scutes are used to quantify Hg contamination.

This review also reveals that in 18 crocodylid species, Hg contamination has never been assessed. Filling this knowledge gap should be a priority, particularly for species

which are strongly impacted by human activities (e.g., mining, oil extraction, and urbanization), which can increase the bioavailability of MeHg in the environment. Furthermore, ecotoxicological studies on potential physiological, behavioral, and reproductive effects of MeHg contamination are needed.

In conclusion, and given their ecological and socio-economic importance, crocodylians are at great risk of Hg contamination, and are excellent bioindicators to global biomonitoring interest for MeHg by the Minamata Convention on Mercury. To ensure robust and standardized assessments of Hg contamination, future studies should consider the methodological points in this review.

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# References

Ackerman JT, Eagles-Smith CA, Herzog MP, Hartman CA, Peterson SH, Evers DC, Jackson AK, Elliott JE, Vander Pol SS, Bryan CE (2016) Avian mercury exposure and toxicological risk across western North America: A synthesis. Sci Total Environ 568:749–769. https://doi.org/10.1016/j.scitotenv.2016.03.071

Albert C, Renedo M, Bustamante P, Fort J (2019) Using blood and feathers to investigate large-scale Hg contamination in Artic seabirds: A review. Environ Res 177:108588. https://doi.org/10.1016/j.envres.2019.108588

Alibardi L (2003) Adaptation to the land: the skin of reptiles in comparison to that of amphibians and endotherm amniotes. J Exp Zool B Mol Dev Evol 298B:12–41. https://doi.org/10.1002/jez.b.24

Alibardi L, Toni M (2007) Characterization of keratins and associated proteins involved in the corneification of crocodilian epidermis. Tissue Cell 39:311–323. https://doi.org/10.1016/j.tice.2007.06.004

Almli B, Mwase M, Sivertsen T, Musonda MM, Flåøyen A (2005) Hepatic and renal concentrations of 10 trace elements in crocodiles (Crocodylus niloticus) in the Kafue and Luangwa rivers in Zambia. Sci Total Environ 337:75–82. https://doi.org/10.1016/j.scitotenv.2004.06.019

Basu N, Stamler CJ, Loua KM, Chan HM (2005) An interspecies comparison of mercury inhibition on muscarinic acetylcholine receptor binding in the cerebral cortex and cerebellum. Toxicol Appl Pharmacol 205:71–76. https://doi.org/10.1016/j.taap.2004.09.009

Beal ER, Rosenblatt AE (2020) Alligators in the big city: spatial ecology of American alligators (Alligator mississippiensis) at multiple scales across an urban landscape. Sci Rep 10:16575. https://doi.org/10.1038/s41598-020-73685-x

Belcher SM, Guillette MP, Robb F, Rock KD (2022) Comparative assessment of blood mercury in American alligators (Alligator mississippiensis) from Coastal North Carolina and Florida. Ecotoxicology 31:1137–1146. https://doi.org/10.21203/rs.3.rs-1495035/v1

Benoit JM, Gilmour CC, Heyes A, Mason RP, Miller CL (2003) Geochemical and biological controls over methylmercury production and degradation in aquatic ecosystems. Am Chem Soc Symp Ser 835:262–297. https://doi.org/10.1021/bk-2003-0835.ch019

Buenfil-Rojas AM, Alvarez-Legorreta T, Cedeño-Vázquez JR (2015) Metals and metallothioneins in Morelet's Crocodile (Crocodylus moreletii) from a transboundary river between Mexico and Belize. Arch Environ Contam Toxicol 68:265–273. https://doi.org/10.1007/s00244-014-0088-5

Buenfil-Rojas AM, Alvarez-Legorreta T, Cedeño-Vázquez JR (2018) Mercury and metallothioneins in blood fractions and tissues of captive Morelet's crocodiles in Quintana Roo, Mexico. Chemosphere 199:630–636. https://doi.org/10.1016/j.chemosphere.2018.01.111

Buenfil-Rojas AM, Alvarez-Legorreta T, Cedeño-Vázquez JR, Rendón-von Osten J, González-Jáuregui M (2020) Distribution of metals in tissues of captive and wild Morelet's crocodiles and the potential of metallothioneins in blood fractions as a biomarker of metal exposure. Chemosphere 244:125551. https://doi.org/10.1016/j.chemosphere.2019.125551

Burger J, Campbell KR, Campbell TS, Shukla T, Jeitner C, Gochfeld M (2005) Use of skin and blood as nonlethal indicator of heavy metal contamination in Northern Water Snakes (Nerodia sipedon). Arch Environ Contam Toxicol 49:232–238. https://doi.org/10.1007/s00244-004-0098-9

Burger J, Gochfeld M, Rooney AA, Orlando EF, Woodward AR, Guillette Jr. LJ (2000) Metals and metalloids in tissues of American alligators in three Florida lakes. Arch Environ Contam Toxicol 38:501–508. https://doi.org/10.1007/s002440010066

Campbell JW, Waters MN, Tarter A, Jackson J (2010) Heavy metal and selenium concentrations in liver tissue from wild American alligator (Alligator mississippiensis) livers near Charleston, South Carolina. J Wildl Dis 46(4):1234–1241. https://doi.org/10.7589/0090-3558-46.4.1234

Carravieri A, Bustamante P, Churlaud C, Cherel Y (2013) Penguins as bioindicators of mercury contamination in the Southern Ocean: Birds from the Kerguelen Islands as a case study. Sci Total Environ 454-455:141–146. https://doi.org/10.1016/j.scitotenv.2013.02.060

Caut S, François V, Bacques M, Guiral D, Lemaire J, Lepoint G, Marquis O, Sturaro N (2019) The dark side of the black caiman: shedding light on species dietary ecology and movement in Agami Pond, French Guiana. PloS One 14(6):e0217239. https://doi.org/10.1371/journal.pone.0217239

Chen CY, Driscoll CT, Eagles-Smith CA, Eckley CS, Gay DA, Hsu-Kim H, Keane SE, Kirk JL, Mason RP, Obrist D, Selin H, Selin NE, Thompson MR (2018) A critical time for mercury science to inform global policy. Environ Sci Technol 52:9556–9561. https://doi.org/10.1021/acs.est.8b02286

Chen CY, Evers DC (2023) Global mercury impact synthesis: Processes in the Southern Hemisphere. Ambio 52(5):827–832. https://doi.org/10.1007/s13280-023-01842-3

Chételat J, Ackerman JT, Eagles-Smith CA, Hebert CE (2020) Methylmercury exposure in wildlife: A review of the ecological and physiological processes affecting contaminant concentration

and their interpretation. Sci Total Environ 711:135117. https://doi.org/10.1016/j.scitotenv.2019.135117

Chin SY, Wilson JD, Cristol DA, Drewett DVV, Hopkins WA (2013) Altered behavior of neonatal northern watersnakes (*Nerodia sipedon*) exposed to maternally transferred mercury. Environ Pollut 176:144–150. https://doi.org/10.1016/j.envpol.2013.01.030

Chumchal MM, Rainwater TR, Osborn SC, Roberts AP, Abel MT, Cobb GP, Smith PN, Bailey FC (2011) Mercury speciation and biomagnification in the food web of Caddo lake, Texas and Louisiana, USA, a subtropical freshwater ecosystem. Environ Toxicol Chem 30(5):1153–1162. https://doi.org/10.1002/etc.477

Compeau GC, Bartha R (1985) Sulphate reducing bacteria: principal methylators of mercury in anoxic estuarine sediment. Appl Environ Microbiol 50:498–502. https://doi.org/10.1128/aem.50.2.498-502.1985

Cordier S, Garel M, Mandereau L, Morcel H, Doineau P, Gosmet-Seguret S, Josse D, White R, Amiel-Tison C (2002) Neurodevelopmental investigation among metylmercury-exposed children in French Guiana. Environ Res 89(1):1–11. https://doi.org/10.1006/enrs.2002.4349

Correira J, Cesar R, Marsico E, Diniz GT, Zorro MC, Castilhos Z (2014) Mercury contamination in alligators (*Melanosuchus niger*) from Mamirauá Reservoir (Brazilian Amazon) and human health risk assessment. Environ Sci Pollut Res 21:13522–13527. https://doi.org/10.1007/s11356-014-3282-0

Crespo-Lopez ME, Arrifano GP, Augusto-Oliveira M, Macchi BM, Lima RR, Nascimento JLM, Souza CBA (2023) Mercury in the Amazon: The danger of a single story. Ecotox Environ Saf 256:114895. https://doi.org/10.1016/j.ecoenv.2023.114895

Delany MF, Bell JU, Sundlof SF (1988) Concentrations of contaminants in muscle of the American alligator in Florida. J Wildl Dis 24(1):62–66. https://doi.org/10.7589/0090-3558-24.1.62

De Paula Gutiérrez BF, Agudelo CAR (2020) Fish as bioindicators: coal and mercury pollution in Colombia's ecosystems. Environ Sci Pollut Res 27:27541–27562. https://doi.org/10.1007/s11356-020-09159-4

De Thoisy B, Hrbeck T, Farias IP, Vasconcelos WR, Lavergne A (2006) Genetic structure, population dynamics, and conservation of Black caiman (*Melanosuchus niger*). Biol Conserv 133:474–482. https://doi.org/10.1016/j.biocon.2006.07.009

Dietz R, Letcher RJ, Desforges J, Eulaers I, Sonne C, Wilson S, Anderson-Ranberg E, Basu N, Barst BD, Bustnes JO, Bytingsvik J, Ciesielski TM, Drevnick PE, Gabrielsen GW, Haarr A, Hylland K, Jenssen BM, Levin M, McKinney MA, Nørregaard RD et al. (2019) Current state of knowledge on biological effects from contaminants on artic wildlife and fish. Sci Total Environ 696:133792. https://doi.org/10.1016/j.scitotenv.2019.133792

Di Marzio A, Gómez-Ramírez P, Barbar F, Lambertucci SA, García-Fernández AJ, Martínez-López E (2018) Mercury in the feathers of bird scavengers from two areas of Patagonia (Argentina) under the influence of different anthropogenic activities: a preliminary study. Environ Sci Pollut Res 25:13906–13915. https://doi.org/10.1007/s11356-018-1333-7

Eagles-Smith CA, Silbergeld EK, Basu N, Bustamante P, Diaz-Barriga F, Hopkins WA, Kidd KA, Nyland JF (2018) Modulators of mercury risk to wildlife and humans in the context of rapid global change. Ambio 47:170–197. https://doi.org/10.1007/s13280-017-1011-x

Eggins S, Schneider L, Krikowa F, Vogt RC, da Silveira R, Maher W (2015) Mercury concentration in different tissues of turtle and caiman species from the Rio Purus, Amazonas, Brazil. Environ Toxicol Chem 34(12):2771–2781. https://doi.org/10.1002/etc.3151

Elsey RM, Lance VA, Campbell L (1999) Mercury levels in Alligator meat in South Louisiana. Bull Environ Contam Toxicol 63:598–603. https://doi.org/10.1007/s001289901022

Evers, D 2018. The effects of methylmercury on wildlife: A comprehensive review and approach for interpretation. In: Dominick A. DellaSala, and Michael I Goldstein (eds.) The Encyclopedia of the Anthropocene, vol. 5, p. 181–194. Oxford: Elsevier. https://doi.org/10.1016/b978-0-12-809665-9.09985-7

Evers DC, Keane SE, Basu N, Buck D (2016) Evaluating the effectiveness of the Minamata Convention on Mercury: Principles and recommendations for next steps. Sci Total Environ 569:888–903. https://doi.org/10.1016/j.scitotenv.2016.05.001

Fujisaki I, Hart KM, Mazzotti FJ, Cherkiss MS, Sartain AR, Jeffery BM, Beauchamp JP, Denton M (2014) Home range and movements of American alligator (*Alligator mississippiensis*) in an estuary habitat. Anim Biotelemetry 2(1):1–10. https://doi.org/10.1186/2050-3385-2-8

Garnett ST (1986) Metabolism and survival of fasting Estuarine crocodiles. J Zool 208:493–502. https://doi.org/10.1111/j.1469-7998.1986.tb01518.x

Gómez-Ramírez P, Shore RF, can den Brink NW, van Hattum B, Bustnes JO, Duke G, Fritsch C, García-Fernández AJ, Helander BO, Jaspers V, Krone O, Matínez-López E, Mateo R, Movalli P, Sonne C (2014) An overview of existing raptor contaminant monitoring activities in Europe. Environ Int 67:12–21. https://doi.org/10.1016/j.envint.2014.02.004

Gustin MS, Evers DC, Bank MS, Hammerschmidt CR, Pierce A, Basu N, Blum J, Bustamante P, Chen C, Driscoll CT, Horvat M (2016) Importance of integration and implementation of emerging and future mercury research into the Minamata Convention. Environ Sci Technol 50:2767–2770. https://doi.org/10.1021/acs.est.6b00573

Haskins DL, Brown MK, Bringolf RB, Tuberville TD (2021) Brown watersnakes (*Nerodia taxispilota*) as bioindicators of mercury contamination in a riverine system. Sci Total Environ 755(2):142545. https://doi.org/10.1016/j.scitotenv.2020.142545

Heaton-Jones TG, Homer BL, Heaton-Jones DL, Sundlof SF (1997) Mercury distribution in American alligators (*Alligator mississippiensis*) in Florida. J Zoo Wildl Med 28(1):62–70

Horai S, Itai T, Noguchi T, Yasuda Y, Adachi H, Hyobu Y, Riyadi AS, Boggs ASP, Lowers R, Guillette Jr. LJ, Tanabe S (2014) Concentrations of trace elements in American alligators (*Alligator mississippiensis*) from Florida, USA. Chemosphere 108:159–167. https://doi.org/10.1016/j.chemosphere.2014.01.031

Hutton J (1989) Movements, home range, dispersal and separation of the size classes in Nile Crocodiles. Amer Zool 29:1033–1049. https://doi.org/10.1093/icb/29.3.1033

Jagoe CH, Arnold-Hill B, Yanochko GM, Winger PV, Brisbin Jr. IL (1998) Mercury in alligators (*Alligator mississippiensis*) in the southeastern United States. Sci Total Environ 213:255–262. https://doi.org/10.1016/s0048-9697(98)00098-9

Janssen SE, Tate MT, Poulin BA, Krabbenhoft DP, DeWild JF, Ogorek JM, Varonka MS, Orem WH, Kline JL (2022) Decadal trends of mercury cycling and bioaccumulation within Everglades National Park. Sci Total Environ 838:156031. https://doi.org/10.1016/j.scitotenv.2022.156031

Kojima LV, Tuberville TD, Parrott BB (2023) Integrating mercury concentrations in American alligators (*Alligator mississippiensis*) with hunter consumption surveys to estimate exposure risk. Environ Toxicol Chem 42(2):525–534. https://doi.org/10.1002/etc.5524

Kom JFM, van der Voet GB, Wolff FA (1998) Mercury exposure of Maroon workers in the small scale gold mining in Suriname. Environ Res 77:91–97. https://doi.org/10.1006/enrs.1998.3835

Kroonenberg S, Wong T, Bijnaar G, Finkie R, Goenopawiro K, Asneel S, Lin-Tsung M, Nanan R, Ramdas K, Sitaram P (2022) Mercury background values in soils and saprolites in the gold-rich greenstone belt of Suriname, Guiana Shield: The role of

parent rock and residual enrichment. Sci Total Environ 848:157631. https://doi.org/10.1016/j.scitotenv.2022.157631

Landler L, Painter MS, Coe BH, Youmans PW, Hopkins WA, Philips JB (2017) High levels of maternally transferred mercury disrupt magnetic responses of snapping turtle hatchlings (Chelydra serpentina). Environ Pollut 11:19–25. https://doi.org/10.1016/j.envpol.2017.04.050

Lavoie RA, Jardine TD, Chumchal MM, Kidd KA, Campbell LM (2013) Biomagnification of mercury in aquatic food webs: A worldwide meta-analysis. Environ Sci Technol 47:13385–13394. https://doi.org/10.1021/es403103t

Lawson AJ, Moore CT, Rainwater TR, Nilsen FM, Wilkinson PM, Lowers RH, Guillette Jr. LJ, McFadden KW, Jodice PGR (2020) Nonlinear patterns in mercury bioaccumulation in American alligators are a function of predicted age. Sci Total Environ 707:135103. https://doi.org/10.1016/j.scitotenv.2019.135103

Lázaro WL, de Oliveira RF, dos Santos-Filho M, da Silva CJ, Malm O, Ignácio ÁRA, Díez S (2015) Non-lethal sampling for mercury evaluation in crocodilians. Chemosphere 138:25–32. https://doi.org/10.1016/j.chemosphere.2015.05.007

Lemaire J, Brischoux F, Marquis O, Mangione R, Bustamante P (2021d) Variation of total mercury concentrations in different tissues of three neotropical caimans: implications for minimally invasive biomonitoring. Arch Environ Contam Toxicol 81:15–24. https://doi.org/10.1007/s00244-021-00846-y

Lemaire J, Brischoux F, Marquis O, Mangione R, Caut S, Brault-Favrou M, Churlaud C, Bustamante P (2022) Relationships between stable isotopes and trace element concentrations in the crocodilian community of French Guiana. Sci Total Environ 837:155846. https://doi.org/10.1016/j.scitotenv.2022.155846

Lemaire J, Bustamante P, Mangione R, Marquis O, Churlaud C, Brault-Favrou M, Parenteau C, Brischoux F (2021b) Lead, mercury, and selenium alter physiological functions in wild caimans (Caiman crocodilus). Environ Pollut 286:117549. https://doi.org/10.1016/j.envpol.2021.117549

Lemaire J, Bustamante P, Marquis O, Caut S, Brischoux F (2021a) Influence of sex, size and trophic level on blood Hg concentrations in Black caiman, Melanosuchus niger (Spix, 1825) in French Guiana. Chemosphere 262:127819. https://doi.org/10.1016/j.chemosphere.2020.127819

Lemaire J, Bustamante P, Olivier A, Lourdais O, Michaud B, Boissinot A, Galán P, Brischoux F (2018) Determinants of mercury concentration in viperine snakes, Natrix maura, in Western Europe. Sci Total Environ 635:20–25. https://doi.org/10.1016/j.scitotenv.2018.04.029

Lemaire J, Marquis O, Bustamante P, Mangione R, Brischoux F (2021c) I got it from my mother: Inter-nest variation of mercury concentration in neonate Smooth-fronted Caiman (Paleosuchus trigonatus) suggest maternal transfer and possible phenotypical effects. Environ Res 194:110494. https://doi.org/10.1016/j.envres.2020.110494

Machkour-M'Rabet S, Hénaut Y, Charruau P, Gevrey M, Winterton P, Legal L (2009) Between introgression events and fragmentation, islands are the last refuge for American crocodile in Caribbean Mexico. Mar Biol 156:1321–1333. https://doi.org/10.1007/s00227-009-1174-5

Maqbool F, Niaz K, Hassan FI, Khan F, Abdollahi M (2017) Immunotoxicity of mercury: Pathological and toxicological effects. J Environ Sci Health C 35(1):29–46. https://doi.org/10.1080/10590501.2016.1278299

Manrico S, Bustamante P, Eulaers I, Malarvannan G, Mendez-Fernandez P, Churlaud C, Blévin P, Hauselmann A, Covaci A, Eens M, Costantini D, Chastel O (2017) Trophic ecology drives contaminant concentrations within a tropical seabird community. Environ Pollut 227:183–193. https://doi.org/10.1016/j.envpol.2017.04.040

Markham KE, Sangermano F (2018) Evaluation wildlife vulnerability to mercury pollution from artisanal and small-scale gold mining in Madre de Dios, Peru. Trop Conser Sci 11. https://doi.org/10.1177/1940082918794320

Marrugo-Negrete J, Durango-Hernández J, Calao-Ramos C, Urango-Cárdenas I, Díez S (2019) Mercury levels and genotoxic effect in caimans from tropical ecosystems impacted by gold mining. Sci Total Environ 664:899–907. https://doi.org/10.1016/j.scitotenv.2019.01.340

Martin S (2008) Global diversity of crocodiles (Crocodilia, Reptilia) in Freshwater. Hydrobiologia 595:587–591. https://doi.org/10.1007/978-1-4020-8259-7_56

Mason RP, Choi AL, Fitzgerald WF, Hammerschmidt CR, Lamborg CR, Soerensen AL, Sunderland EM (2012) Mercury biogeochemical cycling in the ocean and policy implications. Environ Res 119:101–117. https://doi.org/10.1016/j.envres.2012.03.013

Mason RP, Fitzerald WF, Morel FMM (1994) The biogeochemical cycling of elemental mercury: anthropogenic influences. Geochim Cosmochim Acta 58:3191–3198. https://doi.org/10.1016/0016-7037(94)90046-9

Moore LA, Finger Jr. JW, Haskins DL, Elsey RM, Castleberry SB, Glenn TC, Jagoe CH, Brisbin Jr. LL (2022) Tissue distribution of mercury in the bodies of wild American alligators (Alligator mississippiensis) from coastal marsh in Louisiana (USA). Arch Environ Contam Toxicol 83:13–20. https://doi.org/10.1007/s00244-022-00938-3

Morcillo P, Esteban MA, Cuesta A (2017) Mercury and its toxic effects on fish. AIMS Environ Sci 4(3):386–402. https://doi.org/10.3934/environsci.2017.3.386

Nilsen FM, Bowden JA, Rainwater TR, Brunell AM, Kassim BL, Wilkinson PM, Guillette Jr. LJ, Long SE, Schock TB (2019) Examining toxic trace element exposure in American alligators. Environ Int 128:324–334. https://doi.org/10.1016/j.envint.2019.04.035

Nilsen FM, Dorsey JE, Lowers RH, Guillette Jr. LJ, Long SE, Bowden JA, Schock TB (2017a) Evaluating mercury concentrations and body conditions in American alligator (Alligator mississippiensis) at Merritt Island National Wildlife Refuge (MINWR), Florida. Sci Total Environ 607-608:1056–1064. https://doi.org/10.1016/j.scitotenv.2017.07.073

Nilsen FM, Kassim BL, Delaney JP, Lange TR, Brunell AM, Guillette Jr. LJ, Long SE, Schock TB (2017b) Trace element biodistribution in the American alligator (Alligator mississippiensis). Chemosphere 181:343–351. https://doi.org/10.1016/j.chemosphere.2017.04.102

Nilsen FM, Rainwater TR, Wilkinson PM, Brunell AM, Lowers RH, Bowden JA, Guillette LJ, Long SE, Schock TB (2020) Examining maternal and environmental transfer of mercury into American alligator eggs. Ecotoxicol Environ Saf 189:110057. https://doi.org/10.1016/j.ecoenv.2019.110057

Obrist D, Kirk JL, Zhang L, Sunderland EM, Jiskra M, Selin NE (2018) A review of global environmental mercury processes in response to human and natural perturbations: Changes of emissions, climate, and land use. Ambio 47:116–140. https://doi.org/10.1007/s13280-017-1004-9

Oliveira Ribeiro CA, Rouleau C, Pelletier E, Audet C, Tjälve H (1999) Distribution kinetics of dietary methylmercury in the arctic charr (Salvelinus alpinus). Environ Sci Technol 33:902–907. https://doi.org/10.1021/es980242n

Pacheco-Sierra G, Gompert Z, Dominguez-Laso J, Vazquez-Dominguez E (2016) Genetic and morphological evidence of a geographically widespread hybrid zone between two crocodile species, Crocodylus acutus and Crocodylus moreletii. Mol Ecol 25:3484–3498. https://doi.org/10.1111/mec.13694

Peplow D, Augustine S (2014) Neurological abnormalities in a mercury exposed population among indigenous Wayana in Southeast

Suriname. Environ Sci: Processes Impacts 16:2415. https://doi.org/10.1039/c4em00268g

Podar M, Gilmour CC, Brandt CC, Soren A, Brown SD, Crable BR, Palumbo AV, Somenahally AC, Elias DA (2015) Global prevalence and distribution of genes and microorganisms involved in mercury methylation. Sci Adv 1(9):e1500675. https://doi.org/10.1126/sciadv.1500675

Radloff FGT, Hobson KA, Leslie AJ (2012) Characterising ontogenetic niche shifts in Nile crocodile using stable isotope (δ13C, δ15N) analyses of scute keratin. Isot Environ Healt S 48(3):439–456. https://doi.org/10.1080/10256016.2012.667808

Rahm M, Julian B, Lauger A, de Carvolho R, Vale L, Totaram J, Cort KA, Djojodikromo M, Hardjoprajitno M, Neri S, Vieira R, Watanabe E, do Carmo Brito M, Miranda P, Paloeng C, Moe Soe Let V, Crabbe S, Calmel M (2015) Monitoring the impact of gold mining on the forest cover and freshwater in the Guiana Shield. Reference year 2014. REDD+ for Guiana Shield Project and WWF Guianas. pp. 60.

Rainwater TR, Wu TH, Finger AG, Cañas JE, Yu L, Reynold KD, Coimbatore G, Barr B, Platt SG, Cobb GP, Anderson TA, McMurry ST (2007) Metals and organochlorine pesticides in caudal scutes of crocodiles from Belize and Costa Rica. Sci Total Environ 373:146–156. https://doi.org/10.1016/j.scitotenv.2006.11.010

Renedo M, Bustamante P, Tessier E, Pedrero Z, Cherel Y, Amouroux D (2017) Assessment of mercury speciation in feathers using species-specific isotope dilution analysis. Talanta 174:100–110. https://doi.org/10.1016/j.talanta.2017.05.081

Rivera SJ, Pacheco LF, Achá D, Molina CI, Miranda-Chumacero G (2016) Low total mercury in Caiman yacare (Alligatoridae) as compared to carnivorous, and non-carnivorous fish consumed by Amazonian indigenous communities. Environ Pollut 218:366–371. https://doi.org/10.1016/j.envpol.2016.07.013

Rumbold DG, Fink LE, Laine KA, Niemczyk SL, Chandrasekhar T, Wankel SD, Kendall C (2002) Levels of mercury in alligators (Alligator mississippiensis) collected along a transect through the Florida Everglades. Sci Total Environ 297:239–252. https://doi.org/10.1016/s0048-9697(02)00132-8

Salazar-Pammo AC, Achá D, Miranda-Chumacero G (2021) Preferential liver accumulation of mercury explains low concentrations in muscle of Caiman yacare (Alligatoridae) in Upper Amazon. Bull Environ Contam Toxicol 106:264–269. https://doi.org/10.1007/s00128-020-03081-8

Santos X, Navarro S, Campos JC, Sanpera C, Brito JC (2018) Stable isotopes uncover trophic ecology of the West African crocodile (Crocodylus suchus). J Arid Environ 148:6–13. https://doi.org/10.1016/j.jaridenv.2017.09.008

Scheuhammer AM, Meyer MW, Sandheinrich MB, Murray MW (2007) Effects of environmental methylmercury on the health of wild birds, mammals, and fish. Ambio 36(1):12–18. https://doi.org/10.1579/0044-7447(2007)36[12:eoemot]2.0.

Schneider L, Belger L, Burger J, Vogt RC, Jeitner C, Peleja JRP (2011) Assessment of non-invasive techniques for monitoring mercury concentrations in species of Amazon turtles. Toxicol Environ Chem 93(2):238–250. https://doi.org/10.1080/02772248.2010.517627

Schneider L, Eggins S, Maher W, Vogt RC, Krikowa F, Kinsley L, Eggins SM, Da Silveira R (2015) An evaluation of the use of reptile dermal scutes as a non-invasive method to monitor mercury concentrations in the environment. Chemosphere 119:163–170. https://doi.org/10.1016/j.chemosphere.2014.05.065

Schneider L, Peleja RP, Kluczkovski Jr. A, Freire GM, Marioni B, Vogt RC, da Silveira R (2012) Mercury concentration in the Spectacled Caiman and Black Caiman (Alligatoridae) of the Amazon: Implications for Human Health. Arch Environ Contam Toxicol 63:270–279. https://doi.org/10.1007/s00244-012-9768-1

Siqueira GW, Aprile F, Irion G, Braga EC (2018) Mercury in the Amazon basin: Human influence or natural geological pattern? J South Am Earth Sci 86:193–199. https://doi.org/10.1016/j.jsames.2018.06.017

Somaweera R, Nifong J, Rosenblatt A, Brien ML, Combrink X, Elsey RM, Grigg G, Magnusson WE, Mazzotti FL, Pearcy A, Platt SG, Shirley MH, Tellez M, van der Ploeg J, Webb G, Whitaker R, Webber BL (2020) The ecological importance of crocodylians: towards evidence-based justification for their conservation. Biol Rev 95(4):936–959. https://doi.org/10.1111/brv.12594

Tan SW, Meiller JC, Mahaffey KR (2009) The endocrine effects of mercury in humans and wildlife. Crit Rev Toxicol 39(3):228–269. https://doi.org/10.1080/10408440802233259

Thirion F, Tellez M, Van Damme R, Bervoets L (2022) Trace element concentrations in caudal scutes from Crocodylus moreletii and Crocodylus acutus in Belize in relation to biological variables and land use. Ecotoxicol Environ Saf 231:113164. https://doi.org/10.1016/j.ecoenv.2022.113164

Trillanes CE, Pérez-Jiménez JC, Rosíles-Martínez R, González-Jáuregui M (2014) Metals in caudal scutes of Morelet's crocodile (Crocodylus moreletii) from the Southern Gulf of Mexico. Bull Environ Contam Toxicol 93:423–428. https://doi.org/10.1007/s00128-014-1349-8

United Nations Environment Programme (2019) Global mercury Assessment 2018. UN Environment Programme, Chemicals and Health Branch Geneva, Switzerland.

United Nations Environment Programme (2013) Minamata convention on mercury: text and annexes.

Vieira LM, Nunes V, da S, Amaral MC, do A, Oliveira AC, Hauser-Davis RA, Campos RC (2011) Mercury and methyl mercury ratios in caimans (Caiman crocodilus yacare) from the Pantanal area, Brazil. J Environ Monit 13:280–287. https://doi.org/10.1039/c0em00561d

WHO, World Health Organization (2011) WHO Technical Report Series 959, pp.105.

Webb GKW, Hollis GJ, Manolis SC (1991) Feeding, growth, and food conversion rates of wild juvenile Saltwater Crocodiles (Crocodylus porosus). J Herpetol 25(4):462–473. https://doi.org/10.2307/1564770

Wolfe MF, Schwarzbach S, Sulaiman RA (1998) Effects of mercury on wildlife: A comprehensive review. Environ Toxicol Chem 17(2):146–160. https://doi.org/10.1002/etc.5620170203

Xu Q, Fang S, Wang Z, Wang Z (2006) Heavy metal distribution in tissues and eggs of Chinese Alligator (Alligator sinensis). Arch Environ Contam Toxicol 50:580–586. https://doi.org/10.1007/s00244-005-1018-3

Yanochko GM, Jagoe CH, Brisbin Jr. IL (1997) Tissue mercury concentrations in Alligators (Alligator mississippiensis) from the Florida Everglades and the Savannah River site, South Carolina. Arch Environ Contam Toxicol 32:323–328. https://doi.org/10.1007/s002449900192