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REVIEW

Pan-oceanic distribution of mercury (Hg) in sea turtles: a review

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ABSTRACT: With no known biological function, mercury (Hg) is highly toxic, bio-accumulates, and biomagnifies up the food web. Long-living marine animals, such as sea turtles, can be exposed to Hg in the oceans. The wide distributions of these reptiles and lifespans compatible with Hg residence time in ocean surface waters (approximately 30 yr) makes them reliable biological monitors of the long-term changes in Hg concentrations in the oceans. Taking this into consideration, we conducted a thorough review of studies to compare the concentrations of Hg in the 7 species of sea turtles distributed in different regions of the Atlantic, Pacific, and Indian Oceans and the Mediterranean Sea. Hg concentrations in muscle and scutes of *Chelonia mydas* were highest in the South Atlantic, whereas the highest concentrations found in *Caretta caretta* occurred in the Mediterranean Sea. The differences could be associated with the feeding habits of each species and the characteristics of the environment, such as the oligotrophic nature of the water and the lower productivity in the Mediterranean Sea. Unfortunately, few studies exist for the other 5 sea turtles (*Dermochelys coriacea*, *Eretmochelys imbricata*, *Lepidochelys olivacea*, *L. kempii*, and *Natator depressus*), which hampers a more detailed regional or ecological comparison among species. The results found in this review reveal information gaps that should be filled through more numerous studies focused on different oceanic regions and species.

KEY WORDS: Marine turtles · Biomagnification · Pollution · Sentinel species · Bioindicator

1. INTRODUCTION

Environmental contamination is considered one of the greatest challenges facing modern human society (Ali & Khan 2017). Rapid industrialization and urbanization have increased transport rates and mobilization of trace metals in aquatic systems, and mercury (Hg) levels in the upper ocean have tripled since the beginning of the industrial revolution (Casselman 2014, Ali et al. 2019). Trace metals are often listed as priority pollutants in environmental safety assessments (USEPA 2007), and there is a high regulatory interest in highly toxic metals such as Hg (Grillitsch & Schiesari 2010). Hg is considered a pollutant of global importance, due to its long residence time in oceanic surface waters (approximately 30 yr) and in the atmosphere (several months to 1 yr) (Driscoll et al. 2013), which allows its transport to remote places including the Arctic and Antarctic (UNEP 2013). Moreover, organic forms of Hg (e.g. methyl-Hg) are highly toxic, bioaccumulate within organisms, and biomagnify up trophic chains (Chen et al. 2012, Driscoll et al. 2013).

Hg occurs naturally in Earth's biogeochemical systems, but centuries of human industrial activities, mining, and burning of fossil fuels have mobilized

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large amounts of Hg from terrestrial reservoirs to the atmosphere and oceans (Selin 2009, Gworek et al. 2016). Recent modeling of global Hg distribution showed that approximately 49% of the global deposition of Hg in the inorganic form (Hg^{2+}) occurs over tropical oceans (Horowitz et al. 2017, Streets et al. 2017). However, the average Hg concentration in the oceans is not homogeneous; it is higher in the Mediterranean Sea (2.5 pM) and the North Atlantic (2.4 pM) than in the South Atlantic (1.7 pM) and the Pacific Ocean (1.2 pM) (Selin 2009). These differences could be associated with different atmospheric deposition and other Hg fluxes resulting from lateral and vertical seawater flow, particulate settling, and evasion (sea-air transfer) that vary substantially in relative importance across different geographic regions (Sunderland & Mason 2007). Thus, the impact of anthropogenic Hg emissions on oceanic biota is also not uniform (Lamborg et al. 2014).

The complexity of Hg cycling in the ocean makes it challenging to predict exposure levels at higher trophic levels from environmental concentrations alone (Gustin et al. 2016). Therefore, identifying appropriate bioindicators based on their relationship with sensitive ecosystems is a critical first step in assessing the risk to ecological and human health, and in response to the Hg monitoring responsibilities under the Minamata Convention (Gustin et al. 2016, Evers et al. 2018b).

Sea turtles have been suggested as potential bioindicator species to monitor Hg distribution in the oceans, mainly because of their long lifespan and global distribution (Evers et al. 2018a). However, species-specific ecological traits, such as migration and ontogenetic shifts in diet, can confound the interpretation of Hg accumulation in these animals and makes the association of Hg body burdens with habitat difficult (Anan et al. 2002, Miguel & de Deus Santos 2019). The 7 species of marine turtles are loggerhead *Caretta caretta*, green *Chelonia mydas*, hawksbill *Eretmochelys imbricata*, Kemp's ridley *Lepidochelys kempii*, olive ridley *L. olivacea*, leatherback *Dermochelys coriacea*, and flatback *Natator depressus*, and each shows differences that are typically associated with life-history traits (particularly size), habitat use, and trophic status (Figgener et al. 2019). Both diet and distribution are important factors when assessing Hg concentrations in sea turtles. Thus, the evaluation of these 2 factors is extremely important to understand how these organisms accumulate Hg in different regions of the oceans, in addition to the possible variations of concentrations because of greater Hg emissions from both anthropogenic and natural sources.

Since average Hg concentrations are different among ocean regions and the distribution and lifespan of sea turtles lead to high exposure to Hg, this review aims to assess the Hg accumulation in sea turtle species worldwide and to evaluate the use of these organisms as indicators of Hg in the oceans. Specifically, we compared Hg concentrations reported in tissues (e.g. muscle, scutes) of multiple sea turtle species and selected those (*C. caretta* and *C. mydas*) with enough data to identify the potential traits (e.g. habitat, diet, and life stage) that better explain Hg differences across species and oceanic area.

2. MATERIALS AND METHODS

Using electronic databases including Web of Science (https://clarivate.com/webofsciencegroup/solutions/web-of-science/), Science Direct (https://www.sciencedirect.com), Google Scholar (https://scholar.google.com), and Scopus (https://www.scopus.com), we searched for studies reporting Hg concentrations in at least 1 of the 7 species of sea turtles.

Key words included common names and scientific names of sea turtle species (e.g. 'green turtle', '*Chelonia mydas*', 'loggerhead turtle', '*Caretta caretta*', etc.), 'Hg', 'mercury', 'biomonitoring', 'metal', 'heavy metal', 'trace metals', 'bioaccumulation', and 'biomagnification'. We also checked for relevant studies in the bibliographies of all articles selected. For comparison analysis, we considered only the studies with Hg concentrations reported for liver, kidney, muscle, and/or scutes. We did not use studies reporting Hg concentrations in other tissues (e.g. egg, salt gland, bone, fat, blood, intestine, yolked follicles, salt gland secretions, and embryo).

2.1. Data collection

The information recorded included authors' names, year of publication, location, species, sample size, tissue type (e.g. liver, kidney, muscle, scute), mean total Hg concentration in dry weight, and animal size (e.g. mean curved carapace length, CCL). All collected data are presented in Tables S1–S6 in the Supplement at www.int-res.com/articles/suppl/n049p175_supp.pdf. When animal size was reported as straight carapace length (SCL), a transformation to CCL was conducted using the following formulas for each species: *C. mydas* = –0.028 + 1.051 (SCL)

(Bjorndal & Bolten 1989), *C. caretta* = 1.88 + 1.053 (SCL) (Bjorndal et al. 2000), *Lepidochelys olivacea* = (SCL – 9.244)/0.818 (Whiting et al. 2007), *L. kempii* = (SCL – 0.346)/0.948 (Coyne 2000), and *Eretmochelys imbricata* = (SCL − 0.449)/0.935 (Wabnitz & Pauly 2008). For *Dermochelys coriacea* and *Natator depressus*, a transformation was not necessary since all data were reported as CCL.

Sea turtle individuals were classified as juvenile, sub-adult, and adult for each species according to Dodd (1988) for *C. caretta*, Jensen et al. (2016) for *C. mydas*, Reichart (1993) for *L. olivacea*, Márquez (1994) for *L. kempii*, Witzell (1983) for *E. imbricata*, and Eckert et al. (2012) for *D. coriacea.* Unfortunately, there were not enough studies in the case of *N. depressus*. Studies were grouped by oceanic area of sampling including North Atlantic (NA), South Atlantic (SA), Mediterranean Sea (MED), Indian Ocean (IO), North Pacific (NP), and South Pacific (SP).

We recorded the mean value of total Hg concentrations in liver, kidney, muscle, and scute tissues as reported in each study. When Hg concentrations were reported as medians, a conversion was performed using Eq. (1) according to Wan et al. (2014):

$$\text{Mean estimation} = (\text{min} + 2\times\text{median} + \text{max})/4 \quad (1)$$

The reported mean Hg concentration for each tissue was used as an observation to test differences among factors for *C. mydas* and *C. caretta*. All Hg concentrations are reported in ng g^{-1} on a dry weight basis. When necessary, Hg concentrations were converted from wet weight to dry weight using the moisture content of the respective tissue as reported by the respective study. When tissue moisture content was not reported, we assumed a value of 75% for liver, 66% for kidney, and 80% for muscle tissues, according to Garcia-Fernandez et al. (2009). For scute tissues, a value of 29.1% was used according to Perrault et al. (2017).

2.2. Statistical analysis

Statistical analyses were performed using R 4.1.2 (R Development Core Team 2021). Normality assumptions were tested using the Shapiro-Wilk test. Parametric ANOVAs were used to test differences in log-transformed Hg concentrations among factors (e.g. species, year, and oceanic areas) followed by a post hoc Tukey test when necessary. The nonparametric Kruskal-Wallis test was used when data did not meet parametric test assumptions. To improve comparability of Hg concentrations among sea turtles of different sizes, and among sites, we normalized Hg levels (Hg_{norm}) by dividing the reported Hg levels by the average animal size (CCL) for the respective sample pool (Scudder Eikenberry et al. 2015). Normalized Hg levels remove the effect of size on variation in Hg among oceanic areas, improving the interpretation of observed differences. All tests were conducted assuming a significance level of 95% (values were considered significant at $p < 0.05$). Principal component analysis (PCA) was performed to describe variations in log-transformed Hg level as function of selected factors (CCL, oceanic area, tissue) of *C. mydas* and *C. caretta*. PCA was also used to graphically describe the relationship of Hg concentration with factors such as species (*C. mydas* and *C. caretta*), CCL, and oceanic area.

3. RESULTS

Between 1980 and 2020, a total of 70 studies reported Hg concentrations in at least 1 of the 7 species of sea turtles (Fig. 1). From these, more than half (n = 45) presented Hg concentration data for at least 1 of the following tissues: liver, kidney, muscle, and scutes. Only 2 species, *Chelonia mydas* and *Caretta caretta*, presented enough data to compare Hg levels among factors. Therefore, these were the species used in our comparative analyses. For other species, Table S7 describes reported Hg levels.

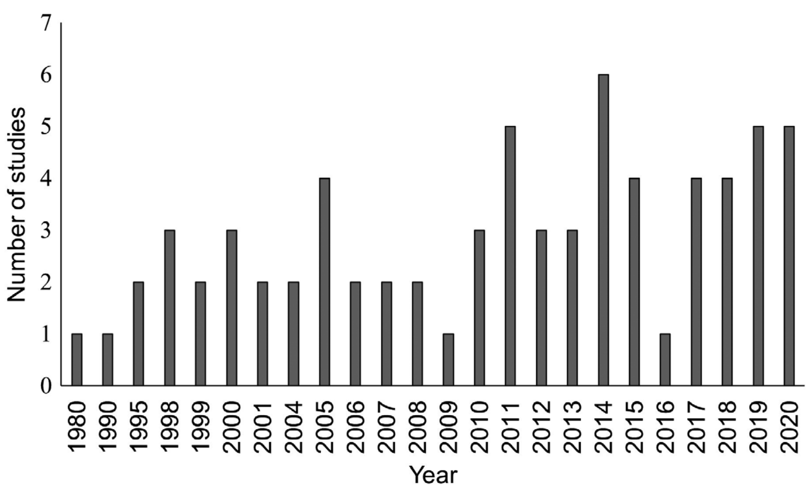

Fig. 1. Worldwide historical record of studies quantifying Hg concentrations in sea turtles from 1980 to 2020. Only years in which studies were published are shown in the graph

3.1. Geographical variations in Hg concentrations

Most papers (n = 43; 61.4%) were published between 2010 and 2020 (Fig. 1) and the oceanic area with the highest number was the North Atlantic (NA) (n = 23), followed by the North Pacific (NP) (n = 18), Mediterranean Sea (MED) (n = 14), South Atlantic (SA) (n = 9), Indian Ocean (IO) (n = 3), and South Pacific (SP) (n = 3) (Fig. 2). Most widespread studies involved *C. mydas*, while *C. caretta* showed a more restricted distribution to the Atlantic Ocean.

Hg was reported most frequently in liver tissue (n = 34), followed by kidney and muscle (n = 26), and scute (n = 17). Many studies reported Hg concentrations in more than 1 tissue type. Other types of samples were reported in less than 30% of the studies and include eggs, salt glands, bone, fat, blood, and embryos, generally with very small numbers of individuals sampled (Table S8). Considering only those studies reporting on at least 1 of the 4 tissues of interest, the literature search resulted in 45 studies.

Because some studies reported Hg concentrations in more than 1 species, the total number of observations for the studies with different species (n = 54) is larger than the total number of studies (n = 45) (Tables S1–S6). In summary, *C. caretta* (46.3%, n = 25) and *C. mydas* (40.7%, n = 22) represented 87% of the observations. The remaining 13.0% (n = 7) were distributed among the other species (*Dermochelys coriacea*, *Eretmochelys imbricata*, *Lepidochelys olivacea*, and *L. kempii*). Only 1 study quantified Hg concentration in eggs and blood of *Natator depressus* (Ikonomopoulou et al. 2011).

To compare Hg levels among oceanic regions, we used results from muscle and scute tissues only. Although the liver and kidney are tissues that also allow comparisons among oceanic regions, we chose to use muscle and scutes because they act as long-term storage for Hg, integrating the exposure over time, and are not directly involved in Hg detoxification processes occurring in other organs (Day et al. 2005, Evers & Sunderland 2019). Geographical varia-

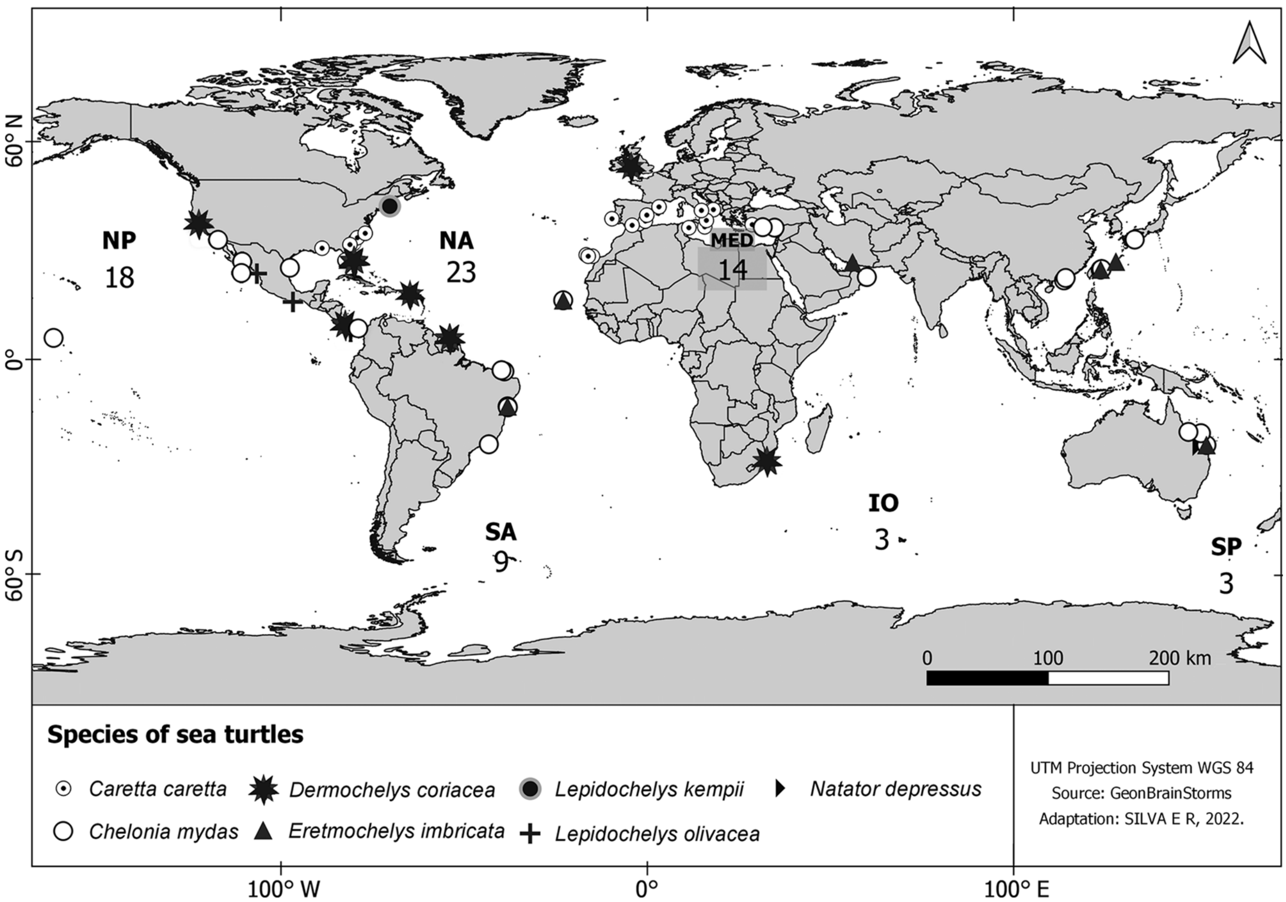

Fig. 2. Geographic distribution of studies quantifying Hg concentrations in sea turtles (n = 70) in the North Atlantic (NA), South Atlantic (SA), Mediterranean Sea (MED), Indian Ocean (IO), North Pacific (NP), and South Pacific (SP). Symbols represent the exact geographical location of each study

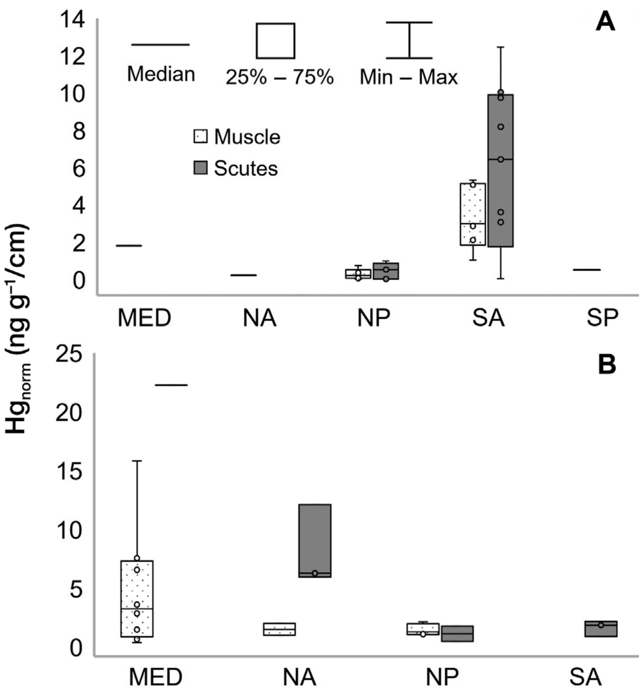

Fig. 3. Total mercury concentrations (Hg_{norm}) in muscle and scutes of (A) *Chelonia mydas* and (B) *Caretta caretta* by region (abbreviations as in Fig. 2). Horizontal lines represent one study for muscles in (A) or scutes in (B). Sample numbers per area were as follows: *C. mydas*, muscle: MED (n = 1), NA (n = 1), NP (n = 6), SA (n = 6), SP (n = 1); scutes: MED (n = 0), NA (n = 0), NP (n = 5), SA (n = 9), SP (n = 0). *C. caretta*, muscle: MED (n = 8), NA (n = 2), NP (n = 4), SA (n = 0), SP (n = 0); scutes: MED (n = 1), NA (n = 3), NP (n = 2), SA (n = 3), SP (n = 0)

tions in Hg levels in muscle and scutes of *C. mydas* and *C. caretta* are shown in Fig. 3.

3.1.1. *Chelonia mydas*

We found significant differences in Hg_{norm} concentrations among oceanic areas for comparisons using scute and muscle tissues. Hg_{norm} levels in muscle were different among oceanic areas (ANOVA: $F_{4,10}$ = 6.17, p = 0.009) and higher for SA compared to NP (post hoc Tukey: p = 0.005) (Fig. 3). Similarly, Hg_{norm} levels in scutes were higher for SA compared to NP (ANOVA $F_{1,12}$ = 7.1, p = 0.02) (Fig. 3).

3.1.2. *Caretta caretta*

We did not find significant differences in Hg_{norm} concentrations among oceanic areas for muscle tissue (ANOVA: $F_{2,11}$ = 0.72, p = 0.5). In contrast, Hg_{norm} levels in scutes were different among oceanic areas (ANOVA: $F_{3,5}$ = 10.97, p = 0.01) and were higher for MED compared to NP (post hoc Tukey: p = 0.02) and SA (post hoc Tukey: p = 0.03). Hg_{norm} levels in scutes were also higher in NA compared to NP (post hoc Tukey: p = 0.03) (Fig. 3).

For oceanic areas where both *C. mydas* and *C. caretta* occur, we found no differences in Hg_{norm} in scutes (ANOVA: $F_{9,9}$ = 1.62, p = 0.24) or muscle (ANOVA: $F_{10,8}$ = 1.9, p = 1.19) between years.

3.2. PCA

According to the PCA, the first 2 principal components (PCs) generated had eigenvalues >1 (λ_i > 1) (Kaiser 1958, Fraga et al. 2016) and were responsible for 74.2% of the variation of the total information on Hg concentrations in sea turtles and different ocean regions. PC1 and PC2 were responsible for 47 and 27.2%, respectively, of the data variations. We found a clear difference regarding *C. mydas* and *C. caretta* between the SA, NP, and MED, in agreement with the differences in concentrations observed in these ocean regions (Fig. 3) and the sizes of the animals included in the studies. This is especially true with Hg concentrations in *C. mydas* from the SA showing an inverse relationship with size (CCL) in all tissues, with juvenile individuals showing higher Hg concentrations (Fig. 4).

4. DISCUSSION

The number of studies quantifying Hg in sea turtles was higher for *Chelonia mydas* and *Caretta caretta*, compared to all other species, as seen in this review and previously for other trace elements (Cortés-Gómez et al. 2017). For other sea turtle species, there is a significant knowledge gap, as few studies have analyzed Hg in the tissues of interest for the present study. The reason for this discrepancy may be related to the fact that *C. mydas* and *C. caretta* are more abundant in coastal areas, facilitating animal capture (Eckert 1993). Moreover, particularly for *Dermochelys coriacea* and *Eretmochelys imbricata*, their endangered status is more critical, reflecting lower population sizes (Mortimer & Donnelly 2008, Wallace et al. 2013) making it difficult to sample these species, thus resulting in a lower number of studies. This scenario is not exclusive to studies on contaminants, but also applies to those involving other research questions. For example, the use of stable isotopes of $\delta^{15}N$ and $\delta^{13}C$, as observed in the

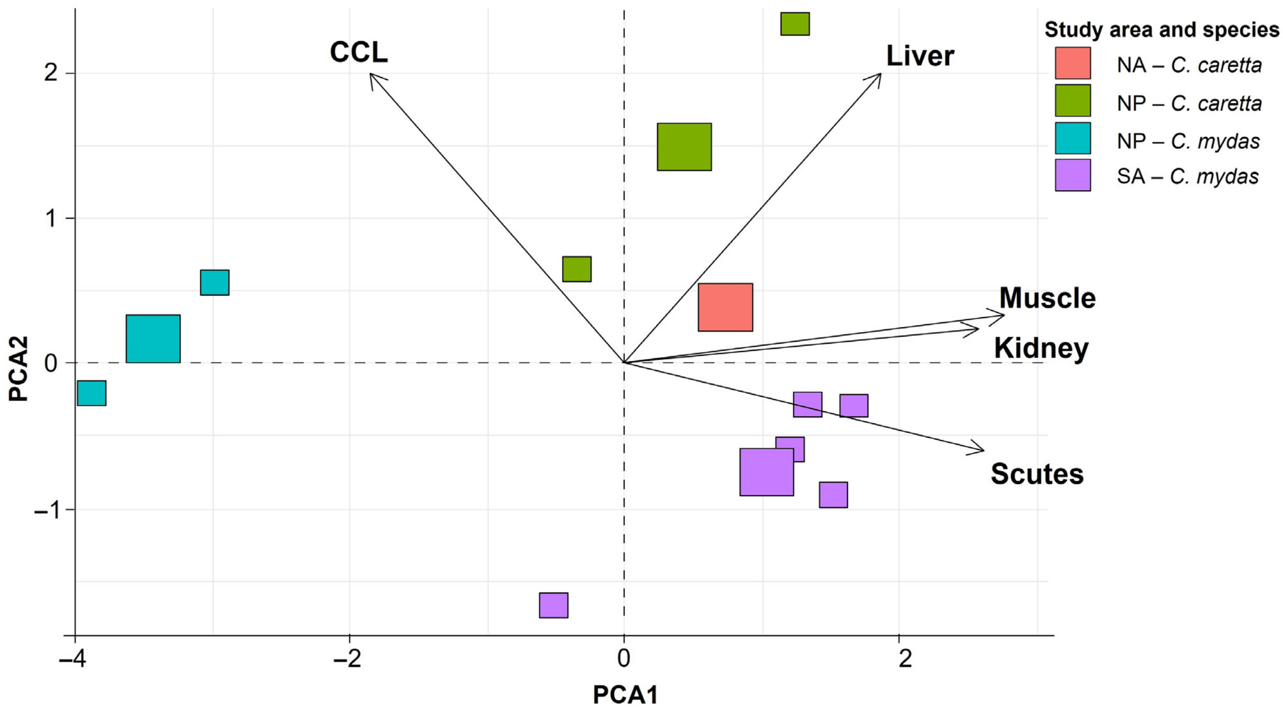

Fig. 4. Principal components analysis (PCA) based on Hg concentrations by region (abbreviations as in Fig. 2), species (*Chelonia mydas* and *Caretta caretta*), tissues (liver, kidney, muscle, and scutes), and curved carapace length (CCL). The 4 larger boxes represent the means of each group

review by Figgener et al. (2019), also showed that the sampling effort tends to be unequal among different species and is also higher in *C. mydas* and *C. caretta.* Therefore, most of the knowledge about the interaction of sea turtles with contaminants, such as Hg, derives from these 2 species.

Both *C. caretta* and *C. mydas* have biological and ecological characteristics that influence their Hg concentrations. Diet and feeding habits are the major pathways of Hg bioaccumulation in sea turtles (Perrault 2014, da Silva et al. 2016). One of the most widely studied examples is the ontogenetic change of diet in green turtles. Juveniles of this species are omnivorous, but adults are almost exclusively herbivorous (Bjorndal 1985, 1997). As a result, Hg concentrations can be inversely related to size (Bezerra et al. 2012). Although the green turtle is not the only sea turtle species that undergoes changes in diet during growth, it is the only one that shifts from omnivory during the juvenile stage to predominantly herbivory when adult, which explains the clearer relationship between diet and Hg concentrations (Sakai et al. 2000, Kampalath et al. 2006, Bezerra et al. 2014, 2015, Rodriguez et al. 2020).

Variation in Hg concentrations with life-stage shifts in green turtles highlights the importance of foraging items as descriptors of Hg concentrations in organisms; however, environmental factors should also be considered, especially regarding Hg sources and fate in the environment. In the present study, we found that Hg_{norm} levels in scutes from *C. caretta* were higher in the Mediterean Sea compared to other ocean basins. The long-lasting legacy of Hg mining activities, a high density of submarine volcanic emissions, and regional contamination have strongly contributed to the greater seawater Hg concentrations compared to those found in the Pacific and Atlantic Oceans (Selin 2009, Cinnirella et al. 2019, Tseng et al. 2021). According to the current Hg budgets, Hg evasion outputs in the Mediterranean Sea are nearly equal to inputs from atmospheric, riverine, and geogenic resources, resulting in lower variability of Hg concentrations in surface waters. In addition, variation in the thermocline depth also correlates with Hg levels in this area (Tseng et al. 2021).

For decades, many studies have pointed to higher Hg concentrations in Mediterranean marine organisms compared to similar species inhabiting the adjacent North Atlantic Ocean or the Black Sea (Cossa et al. 2012). These discrepancies are particularly noticeable in top predators, such as tuna or marine mammals (Cossa et al. 2012). The oligotrophic nature of the water and the lower productivity in the system are linked to the higher Hg bioaccumulation rate by Mediterranean organisms (Chouvelon et al. 2018).

Our results for *C. caretta* scute tissue also show higher Hg levels in the North Atlantic compared to the North Pacific. This is in accordance with models showing higher concentrations of Hg in the Mediterranean Sea and the North Atlantic, compared to the South Atlantic and the Antarctic Ocean (Lamborg et al. 2002, Gworek et al. 2016).

Other long-living oceanic organisms also present similar Hg accumulation patterns. Evers et al. (2018b) compared the 3 species of bluefin tuna (*Thunnus* spp.) in 6 oceanic regions (North Atlantic, Mediterranean Sea, North Pacific, South Atlantic, South Pacific, and Indian Ocean), and Tseng et al. (2021) evaluated the variation of Hg bioaccumulation in bluefin tuna on a global scale. These authors found significant variation in Hg concentrations among bluefin tuna populations from distant ocean basins, where the highest concentrations of Hg in tuna were in species from Mediterranean regions. The authors also discussed this pattern because of different levels of Hg pollution associated with contrasting ecological structures and circulation patterns across ocean regions (Tseng et al. 2021). Studies targeting cetacean species, especially delphinids (e.g. striped dolphin *Stenella coeruleoalba*, common bottlenose dolphin *Tursiops truncatus*), found that individuals from the Mediterranean Sea presented the highest levels among different oceanic areas (Kershaw & Hall 2019). Thus, the levels of Hg detected in species that use the Mediterranean Sea as a foraging area, such as *C. caretta*, bluefin tunas, and cetaceans, may be higher when compared to individuals of the same species in the Atlantic and Pacific Oceans. These trends are reflected in our results. Although *C. caretta* from the Mediterranean Sea showed higher concentrations in scutes compared with other regions, our results need to be interpreted with caution because only 1 study reported Hg concentrations in scutes in *C. caretta* from the Mediterranean Sea (Casini et al. 2018).

The bioaccumulation of Hg in marine biota results from continuous exposure, mostly from feeding (Gray 2002, Kidd et al. 2011), and a slow rate of metabolic elimination, typical of larger and older animals, which results in an increased body load of Hg (Morel et al. 1998). Anthropogenic factors also play a relevant role in Hg exposure in sea turtles, mainly in coastal areas where anthropogenic activities have the potential to change local environmental concentrations of Hg and, consequently, the Hg contents in the food items consumed by these reptiles (Bezerra et al. 2015, Gworek et al. 2016). When analyzing studies comparing Hg concentrations on a regional scale, such as those by Bezerra et al. (2015) and Barraza et al. (2019), the importance of local sources of anthropogenic contamination along the coast becomes clear, especially in regions where sea turtles feed. Barraza et al. (2019) observed that the anthropogenic activities and pollution in a given region can affect how green turtles accumulate trace metals. Furthermore, Bezerra et al. (2015) compared juvenile green turtles from 2 coastal sites in Brazil, one densely populated and with an extensive industrial zone, and the other with a lower anthropogenic impact. The results of their research showed that both green turtles and their food items (algae and mollusks) presented higher Hg concentrations in the area with more intense anthropogenic sources of Hg. Thus, on a regional scale, it is possible to observe the influence of anthropogenic activities on Hg burdens of sea turtles.

The differences found in this study between the North Pacific and South Atlantic regions using *C. mydas* is another example of the influence of environmental concentrations of Hg in both oceans. Most of the studies with *C. mydas* in the South Atlantic are from southeastern Brazil, the most industrialized region in that country (Marins et al. 2004, Kütter et al. 2022). Thus, the surface waters of this zone may reflect the Hg of anthropic emissions. Likewise, these differences can also be observed in deeper waters. For example, Mason et al. (1998, 2001) and Laurier et al. (2004) reported higher average concentrations of Hg in deeper waters in the South Atlantic compared to the North Pacific.

Other marine organisms such as sea birds have also been shown to reflect regional characteristics on Hg levels. Comparing 2 colonies of Bulwer's petrel *Bulweria bulwerii* between the Atlantic and the Pacific showed that chicks and adults had significantly higher concentrations of Hg in the colonies of the Atlantic than those of the Pacific Ocean (Furtado et al. 2021). Given that this species has no apparent trophic differences, the most likely explanation is that food items consumed by these birds (e.g. fish, squid) in the Atlantic mesopelagic zone have higher Hg levels than in the Pacific (Carravieri et al. 2014, Furtado et al. 2021). Also, these variations may result from a complex interaction of factors, including variation in atmospheric deposition, productivity, and microbial activity, and differences in planktonic communities, as different types of phytoplankton present different rates of bioaccumulation (Zhang et al. 2020).

In the present study, although Hg data span several decades, we did not find a clear pattern of Hg accumulation over time. The limited number of studies with sea turtles and without a continuous monitoring program makes it difficult to observe such patterns. To best track global and regional biotic Hg exposure over time and space, we need to synthesize existing information with new data in a structured and strategic way (Evers & Sunderland 2019). To achieve this, it is extremely important to carry out more studies reporting Hg concentrations in different species of sea turtles using non-invasive methods.

The use of scutes has helped to promote research with sea turtles, mainly because it is a non-invasive method and a tissue that, unlike the liver or kidney, accumulates Hg for a longer time, thus providing a history of Hg accumulation (Schneider et al. 2015). Studies such as those by Vander Zanden et al. (2013) show that the estimated time that scutes can retain several types of resources (e.g. isotopes and other metals) is approximately 0.8 yr in juveniles and 6.5 yr in adults. Furthermore, the stability of Hg in the scute matrix makes this tissue preferable for approximating long-term exposure (Day et al. 2005). Scutes have been shown to be the most effective predictor of Hg concentrations in tissues like the liver, kidney, and muscle (Sakai et al. 2000, Day et al. 2005, Bezerra et al. 2013). Above all, analyzing scute tissues has been a good indicator of Hg concentrations and diet changes in species such as *C. mydas* (Sakai et al. 2000, Bezerra et al. 2013, 2015, Barraza et al. 2019).

Global models will be critical for understanding current needs and prioritizing future patterns (Evers & Sunderland 2019), as well as tracking changes in Hg concentrations of selected bioindicators associated with control measurements of specific Hg sources, or the cumulative effects of measures adopted by agreements, such as the Minamata Convention on Mercury (Davis et al. 2016, Evers et al. 2016). For sea turtles, it is necessary to develop and improve geographically representative modeling and monitoring of Hg levels and Hg compounds in vulnerable populations and the environment (Coulter 2016, Evers et al. 2016). Thus, and according to the information collected through this review, we consider that there are 4 important strategies to be carried out that in the future would allow us to obtain comparable results: (1) using non-invasive methodologies that allow the collection of tissues from living individuals; (2) standardizing the type of tissue used; (3) sampling individuals in the same life-stage classes; and (4) developing intensive sampling strategies able to differentiate the impact of changing environmental conditions on a sub-regional scale. The results and information generated would allow us to have a clear idea about the use of sea turtles as possible monitors of the impact on the coastal and oceanic environments over time.

5. CONCLUSION

The present review highlights the clear imbalance in studies on Hg concentrations among the 7 species of sea turtles. *Chelonia mydas* and *Caretta caretta* are the most studied species; consequently, most of the information and knowledge that is available about the fate of Hg in these reptiles comes from these 2 species, and a broader evaluation, including other species, is urgently needed. There is also a strong bias considering that most of the results in *C. caretta* come from adult females in the nesting stage, which means that behaviors such as aphagia, where sea turtles decrease food intake, can affect the Hg concentrations that females reflect during reproductive periods. Therefore, any potential sex differences in feeding behavior that can affect Hg accumulation are not accounted for and should be considered in future studies.

Studies disproportionately focus on the North Atlantic, followed by the Mediterranean Sea, North Pacific, and South Atlantic. We found an important knowledge gap for the South Pacific where there are no Hg data for scutes of any sea turtle species. Differences in Hg levels between the South Atlantic and the North Pacific regions are due to background differences in Hg availability and not an effect of animal size, as these were removed by normalizing the Hg data. In the same way, differences in Hg concentration in *C. caretta* are associated with differences in the average environmental Hg concentrations reported by different studies, especially for the Mediterranean Sea, which showed higher Hg concentrations and was corroborated by results in other marine organisms such as tuna and marine mammals.

For more endangered and less abundant species, such as *Dermochelys coriacea*, *Eretmochelys imbricata*, *Lepidochelys kempii*, *Natator depressus*, and *L. olivacea*, only limited information is available on Hg accumulation. This is very important considering that some of these species (e.g. *L. kempii* and *N. depressus*) have a very restricted distribution and thus might reflect different Hg burdens from. *D. coriacea* is an essentially oceanic species with limited use of coastal areas and therefore may also present distinct patterns of Hg accumulation. The small number of studies with sea turtles compared to other marine organisms may be related to their status as endangered species, and the absence of commercial importance which reduces commercial captures worldwide and limits sampling to stranded and dead individuals. Therefore, the use of non-invasive techniques such as using scutes for monitoring Hg in sea turtles is critically important to allow for a better sampling design in future studies.

Scute sampling is a relatively recent technique, but it has been shown as a reliable method of Hg monitoring in sea turtles as it can reflect not only feeding behavior but also habitat contamination level. The results from the present study for *C. caretta* and *C. mydas* show that these species probably can be used as monitors of Hg concentrations in the oceans. However, as mentioned previously, the current data available are based on a few studies and should be interpreted with caution. Overall, sea turtles present a moderate level of Hg accumulation that reflects regional backgrounds and species-specific feeding behavior. As species, sea turtles inhabit many areas in very distinct oceanic and coastal regions which truly characterizes them as ocean sentinels. We strongly recommend an increased effort to protect and use these animals as target species for the monitoring of Hg pollution using non-lethal scute sampling techniques.

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