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Mercury contamination and potential health risk to French seabirds: A multi-species and multi-site study

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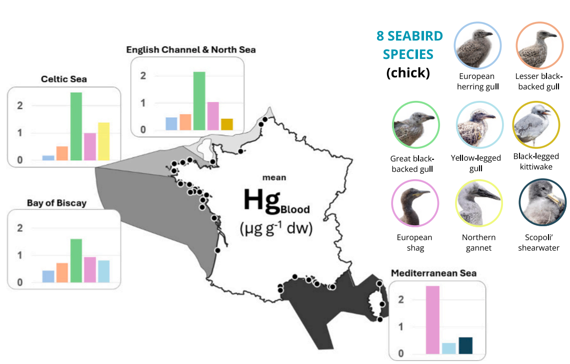
HIGHLIGHTS

- Blood Hg was analysed in chicks of eight seabird species from 32 sites in France.
- Influences of extrinsic and intrinsic factors on Hg concentrations were evaluated.
- Feeding ecology, especially $\delta^{15}N$ values was the main driver of Hg variation.
- No strong geographical difference in seabird Hg contamination was reported.
- According to Hg toxicity threshold, 74% of chicks were categorized as no risk.

GRAPHICAL ABSTRACT



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ABSTRACT

Mercury (Hg) is a naturally occurring highly toxic element which circulation in ecosystems has been intensified by human activities. Hg is widely distributed, and marine environments act as its main final sink. Seabirds are relevant bioindicators of marine pollution and chicks are particularly suitable for biomonitoring pollutants as they reflect contamination at short spatiotemporal scales. This study aims to quantify blood Hg contamination

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Chick
Stable isotopes
Metal
Atlantic
Mediterranean Sea

and identify its drivers (trophic ecology inferred from stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), geographical location, chick age and species) in chicks of eight seabird species from 32 French sites representing four marine subregions: the English Channel and the North Sea, the Celtic Sea, the Bay of Biscay and the Western Mediterranean. Hg concentrations in blood ranged from 0.04 μg g^{-1} dry weight (dw) in herring gulls to 6.15 μg g^{-1} dw in great black-backed gulls. Trophic position ($\delta^{15}N$ values) was the main driver of interspecific differences, with species at higher trophic positions showing higher Hg concentrations. Feeding habitat ($\delta^{13}C$ values) also contributed to variation in Hg contamination, with higher concentrations in generalist species relying on pelagic habitats. Conversely, colony location was a weak contributor, suggesting a relatively uniform Hg contamination along the French coastline. Most seabirds exhibited low Hg concentrations, with 74% of individuals categorized as no risk, and $<$ 0.5% at moderate risk, according to toxicity thresholds. However, recent work has shown physiological and fitness impairments in seabirds bearing Hg burdens considered to be safe, calling for precautional use of toxicity thresholds, and for studies that evaluate the impact of Hg on chick development.

1. Introduction

Mercury (Hg) is an element naturally present in the environment, but anthropogenic activities have contributed to significant releases that well exceed natural emissions (Gworek et al., 2020; Streets et al., 2019). Once in the aquatic environment, Hg in its inorganic form (iHg) is transformed into methylmercury (MeHg) mainly *via* microbial processes (Gworek et al., 2016). In contrast to iHg, MeHg is highly bioavailable and is also very toxic for biota (Sakamoto et al., 2011). MeHg bioaccumulates in the tissues of living organisms over time and biomagnifies within food webs, a process which is particularly exacerbated in marine ecosystems due to more complex food webs and high bioconcentration in first trophic levels (Chételat et al., 2020; Lavoie et al., 2015; Liu, 2012). Furthermore, MeHg induces a wide range of adverse effects, including neurological, endocrine, behavioral, immune and reprotoxic effects, even at low concentrations (*e.g.*, Chastel et al., 2022; Holmes et al., 2009; Kalisińska, 2019; Scheuhammer et al., 2007; Wolfe et al., 1998), with demonstrated effects on wild seabird populations (Goutte et al., 2014a, 2014b).

The Minamata Convention on Mercury was adopted to reduce anthropogenic emissions and thus the risks of Hg exposure to humans and wildlife (https://www.mercuryconvention.org). However, divergences between trends of Hg in marine biota and anthropogenic emissions are increasingly being reported (Lippold et al., 2020; Morris et al., 2022; Tartu et al., 2022; Wang et al., 2019), and the effectiveness of the Minamata Convention on Hg levels in marine predators is still unclear (Médieu et al., 2024). In the marine environment, Hg is highly persistent and has a complex biogeochemical cycle that is influenced by multiple cascade processes that could explain the uncoupling between emissions and biota Hg burdens (Obrist et al., 2018; Sonke et al., 2023; Wang et al., 2019). Global change is also a key driver that could contribute to increasing Hg exposure in biota (Wang et al., 2019). Moreover, reductions in emissions are not predicted to induce strong and quick reductions of environmental concentrations, especially if there is no decisive action to reduce Hg emissions (Schartup et al., 2022). Therefore, Hg is an ongoing and future threat for marine ecosystems and a better understanding of exposure and effects on marine fauna is essential. Article 19 of the Minamata Convention on Mercury calls for increased geographical monitoring of Hg burdens in marine fauna, including marine mammals, sea turtles and seabirds, which are all good bioindicators of Hg contamination of the environment (Evers et al., 2024). In addition, in 2008, the European Union adopted the Marine Strategy Framework Directive (MSFD), a legislative text requiring European member states to assess, achieve or maintain a Good Environmental Status (GES) of their marine waters. The MSFD aims to protect the marine environment against harm caused by chemical contaminants (Descriptor 8), including Hg, and implies monitoring of concentrations in different environmental matrices, and of biological effects. Commonly monitored biota includes fish and invertebrates (notably *Mytilus* and *Crassostrea* spp.), while upper marine predators are largely overlooked (Mille et al., 2023). Contaminant biomonitoring should be multi-sites and include species with diverse trophic ecologies and wide spatial distributions (Wang et al., 2019), but is still sparse in European waters and rarely carried out in marine predators such as seabirds, which hinders the comprehensive assessment of Hg contamination and its risks across food webs.

Seabirds, as long-lived, mid to top predators, can accumulate large Hg quantities and consequently suffer physiological and fitness impairments (reviewed in Ackerman et al., 2016; Chastel et al., 2022; Whitney and Cristol, 2017). Due to their life history characteristics, these birds are relevant spatiotemporal bioindicators of Hg contamination in coastal and oceanic ecosystems (Burger and Gochfeld, 2004; Elliott and Elliott, 2013). Adult seabirds are commonly used to assess Hg contamination through non-lethal sampling of feathers and blood (Albert et al., 2019; Peterson et al., 2019; Renedo et al., 2018). Blood is a relevant matrix to evaluate recent Hg exposure due to its relatively short half-life in this tissue (Monteiro and Furness, 2001a). However, recent works suggest that past Hg exposure during migration and/or overwintering can significantly affect circulating levels during breeding (Carravieri et al., 2023; Lavoie et al., 2015, 2014). This complicates the use of adult seabirds to evaluate local Hg contamination. Moreover, intrinsic traits such as sex (related to variability in feeding strategies and maternal transfer; Ackerman et al., 2020; Carravieri et al., 2014b; Robinson et al., 2012), breeding stage (Tartu et al., 2013; Tavares et al., 2013) and moulting patterns (Bearhop et al., 2000; Carravieri et al., 2014a) can also influence adult blood Hg concentrations. Thus, interpreting Hg concentrations of adults requires detailed knowledge on migration routes, wintering areas, and moulting strategies (Albert et al., 2019; Carravieri et al., 2023, 2014a). In pre-fledging chicks (hereafter chicks), egg-derived Hg resulting from maternal transfer is excreted in down feathers and diluted during growth (Ackerman et al., 2011). In most species, seabird chicks are fed by their parents with food obtained in areas close to the colony, representing a restricted spatiotemporal window. Chicks therefore faithfully represent recent and local Hg contamination of assimilated diet items and are commonly used in Hg monitoring using growing feathers (*e.g.*, Blévin et al., 2013), blood (*e.g.*, Albert et al., 2019; Carravieri et al., 2020, 2017) or both (levels in feathers and blood are tightly correlated; Binkowski et al., 2021). Species can differ in Hg contamination depending on the resources and habitats they use and/or on taxonomic differences in Hg detoxification mechanisms and efficiency (Eagles-Smith et al., 2009; Lucia et al., 2012). Multi-species studies targeting chicks may allow us to assess Hg variability between specific marine compartments and help us disentangle exposure from detoxification.

In Europe, several studies have focused on Hg contamination in seabirds over the last two decades (*e.g.*, Albertos et al., 2020; Goutner et al., 2013; Novotna Kruzikova et al., 2023; Sánchez-Fortún et al., 2020; Sanpera et al., 2007; Szumiło-Pilarska et al., 2017; Zorrozua et al., 2020). However, studies carried out on French seabird communities have mainly targeted the overseas territories: French Guiana (six species, Sebastiano et al., 2017, 2016), Clipperton Island (six species, Bustamante et al., 2023), Reunion Island and Glorioso Archipelago (10 species, Kojadinovic et al., 2007a, 2007b, 2007c), sub-Antarctic islands and Antarctica (33 species, Blévin et al., 2013; Carravieri et al., 2020, 2018, 2017, 2014c; Cherel et al., 2018; Renedo et al., 2018). Metropolitan France hosts >225,000 breeding pairs of seabirds belonging to 28 species (GISOM, 2023), yet our knowledge about their Hg contamination is still very limited (four species in Southwestern France: Jouanneau et al., 2022; Zorrozua et al., 2020; four species in the English Channel: Binkowski et al., 2021; Lemesle et al., 2024).

Here, we quantified Hg concentrations in the blood of chicks of eight seabird species (five Charadriiformes, two Suliformes and one Procellariformes) from 32 sites across four marine subregions in metropolitan France (English Channel and North Sea, Celtic Sea, Bay of Biscay and Western Mediterranean Sea). The wide spatial distribution of these species on the French coasts, particularly *Laridae* species, enables multiple spatial comparisons. Moreover, this multi-species sampling represents a wide range of feeding strategies, including generalist and specialist species, using coastal and/or pelagic feeding habitats. Here, we used carbon (δ^{13}C) and nitrogen (δ^{15}N) stable isotope values as proxies of feeding ecology (Bond and Jones, 2009; Lourenço et al., 2015). Specifically, δ^{13}C values indicate feeding habitats (values below −25 ‰ reflect a primarily terrestrial/freshwater diet, values included between −25 ‰ and −18 ‰ suggest a mixt of freshwater/marine diet, and finally values above −18 ‰ indicate a primarily marine diet) (Bearhop et al., 1999; Hobson, 1990; Oppel and Powell, 2010) and δ^{15}N values are a proxy of trophic position, increasing by around 3.4 ‰ at each trophic step (Hobson et al., 1994; Post, 2002).

This large multi-species and multi-site study aimed to 1) document blood Hg concentrations; 2) determine extrinsic (site and trophic ecology) and intrinsic (chick age and species) factors driving variation in Hg concentrations; and 3) discuss potential health risks to French seabirds in relation to known Hg toxicity thresholds. Due to Hg biomagnification processes, we expected that i) species and individuals feeding in marine habitats (high δ^{13}C values) at higher trophic positions (high δ^{15}N values) to have higher blood Hg concentrations than species feeding in terrestrial habitats (low δ^{13}C values) and feeding at lower trophic positions (low δ^{15}N values); and ii) Mediterranean populations to have the highest Hg concentrations, as previously shown in large scale studies of lower trophic level organisms on the French coastline (Briant et al., 2017; Claisse et al., 2001; Mauffret et al., 2023).

2. Materials and methods

2.1. Sample collection

Fieldwork was conducted at 32 sites along the coastline of metropolitan France (including Corsica) in the summers of 2019, 2020 and 2021 during the chick-rearing period (Fig. 1). Twenty sites were sampled in three marine subregions of the Atlantic coast (English Channel and North Sea, Celtic Sea and Bay of Biscay) as well as 12 sites along the Mediterranean coast (Western Mediterranean marine subregion). Eight species were sampled: five *Laridae* species (European herring gulls *Larus argentatus argentatus*, lesser black-backed gulls *L. fuscus graellsi*, great black-backed gulls *L. marinus*, yellow-legged gulls *L. michahellis*, and black-legged kittiwakes *Rissa tridactyla* ("herring gulls", "lesser b-b gulls", "great b-b gulls", "yellow-l. gulls" and "kittiwakes", respectively, hereafter)), European shags *Gulosus aristotelis* ("shags" hereafter), northern gannets *Morus bassanus* ("gannets" hereafter) and Scopoli's shearwaters *Calonectris diomedea* ("shearwaters" hereafter). Adults of these eight species forage in areas close to the colony to feed their chicks but provide diverse diets (*i.e.*, individual birds can be specialists or generalists) from different habitats (terrestrial, coastal, oceanic, benthic or/and epipelagic environments) depending on species (Table S1). In total, 849 well-feathered chicks were captured before fledging, measured, blood sampled and ringed (n = 2–38 individuals per species and site), except for gannet chicks, which were caught just after fledging using a dip net from a boat. All other species

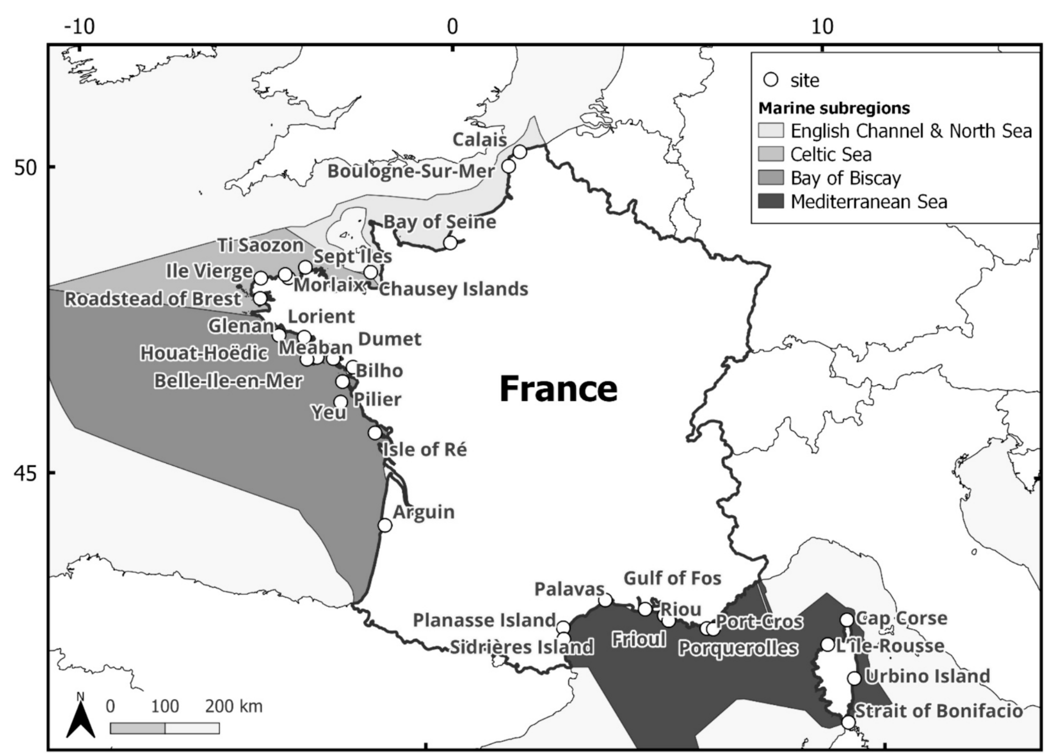

Fig. 1. Sampling sites in different marine subregions of the metropolitan French coast. Circles represent sampling colonies. Marine subregions are represented by different shades of grey.

were caught by hand around or in the nest (shags, *Laridae* species) or burrow (shearwaters). Biometric measurements were taken using a Pesola spring balance (body mass), a sliding calliper with a 0.1 mm accuracy for skull (head + bill), beak (thickness and length) and tarsus length, and a ruler with a 1 mm accuracy was used for wing length. Blood (2–3 ml depending on the species size, <1% of the body mass) was collected with heparinized syringes and 23 or 25-gauge needles from the brachial vein. Blood samples were transferred into Eppendorf® tubes and stored in a cool box during fieldwork. Plasma and red blood cells (RBC) were separated by centrifugation at 4000 rpm for 6 min at 4 °C within 2 to 6 h after sampling. Where possible, RBC and plasma samples were stored in liquid nitrogen until their final storage in a freezer (−20 °C for RBC).

2.2. Mercury analyses

Due to the relatively short half-life of Hg in blood (estimated to be less than a week for chicks of Cory's shearwater *Calonectris borealis*, Monteiro and Furness, 2001b), blood is commonly used to quantify Hg concentrations over a recent temporal scale (Albert et al., 2019). In

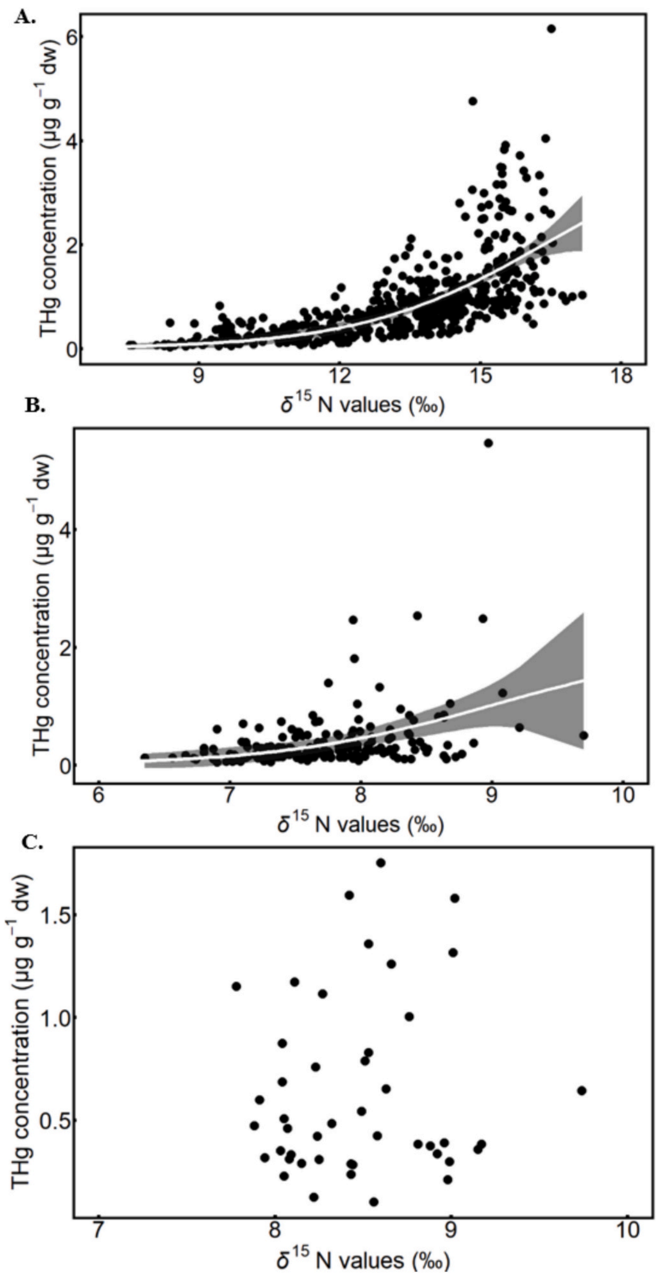

Fig. 2. Mercury concentrations (μg g^{-1} dw) association with $\delta^{15}N$ values (‰) for each dataset (A. Atlantic, B. Mediterranean yellow-legged gull, C. Mediterranean Scopoli's shearwater). The white line represents a fitted non-linear logistic equation $y = \frac{asym}{\left(1+e^{\left[\frac{(xmid-x)}{scal}\right]}\right)}$ with 95% confidence interval in grey.

Estimated parameters are $\beta \pm$ SE: A. *asym* 4.08 ± 1.54, *xmid* 16.42 ± 1.40 and *scal* 2.00 ± 0.33 and $\Delta AICc_{nls\text{-}null} = 348$ for the Atlantic dataset and B. *asym* 2.03 ± 1.63, *xmid* 9.00 ± 1.24 and *scal* 0.81 ± 0.32 and $\Delta AICc_{nls\text{-}null} = 27$ for the Mediterranean yellow-legged gull dataset.

blood, total Hg concentrations are a close approximation of MeHg concentrations (~100%, Renedo et al., 2021). Furthermore, Hg in blood is mainly associated with the cellular fraction (Bond and Robertson, 2015; Renedo et al., 2018). We will thus use the term "blood" to refer to RBC hereafter, unless otherwise specified. Blood was freeze-dried and homogenised to powder and Hg was quantified in subsamples of this powder (mean ± SD, 1.38 ± 0.72 mg dry weight (dw)) using an Advanced Mercury Analyser (®Altec AMA 254 spectrophotometer) at the LIENSs laboratory. Hg was quantified in duplicate or triplicate (n = 1705 subsamples from 849 individuals) such that the relative standard deviation was below 10% (mean ± SD: 1.67 ± 0.02%). The retained concentration is the mean value of replicate measurements. Two certified reference materials for trace elements were analysed under the same conditions of the samples: DOLT-5 (dogfish liver, Hg-certified value: 0.44 ± 0.18 μg g^{-1} dw from National Research Council of Canada (NRCC), Yang et al., 2014) or TORT-3 (lobster hepatopancreas, Hg-certified value: 0.29 ± 0.02 μg g^{-1} dw from NRCC, Willie et al., 2013). Recovery rates (± SD) were 98.3 ± 0.90% (DOLT-5) and 103.3 ± 4.3% (TORT-3). Blanks were measured before each run and the limit of detection of the AMA was 0.1 ng. Hg concentrations are expressed in μg g^{-1} dw.

2.3. Stable isotope analyses

Both $\delta^{13}C$ and $\delta^{15}N$ values have a rapid turnover in blood, up to one month, providing short-term insights on trophic ecology (Bearhop et al., 2002; Lourenço et al., 2015; Ogden et al., 2004; Vander Zanden et al., 2015). Stable isotope analyses were carried out at the LIENSs laboratory. The relative abundance of carbon and nitrogen stable isotopes were measured from subsamples of blood powder (0.36 ± 0.09 mg, n = 849) packed into tin containers. Isotopic percentages were quantified with a continuous flow mass spectrometer (Thermo Scientific Delta V Plus®) coupled to an elemental analyser (Thermo Scientific EA Flash®). Isotopic data were defined by the following equation: $\delta^{13}C$ or $\delta^{15}N$ (‰) = $((Rsample/Rstandard) - 1) \times 1000$ where R represents the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ ratio. Isotopic values were expressed as standard delta (δ) notations based on international standards, Vienna PeeDee Belemnite and atmospheric nitrogen (N_2) for $\delta^{13}C$ and $\delta^{15}N$, respectively. Three certified reference materials (USGS-61, USGS-62 and USGS-63, caffeine) were analysed to check the accuracy (Schimmelmann et al., 2016). The analytical precision was <0.10 ‰ for both $\delta^{13}C$ and $\delta^{15}N$ values.

2.4. Statistical analyses

All analyses and data representation were carried out using R (version 4.2.2., R Core Team, 2020). Species sampled at only one site (kittiwakes and gannets), as well as data from sites with less than five sampled individuals (*i.e.*, lesser b-b gulls from Morlaix, great b-b gulls from Yeu and yellow-l. gulls from Pietra Island) were used only for descriptive statistics, but were excluded from regression analyses (Table S2). Six individuals presented very low $\delta^{13}C$ values (herring gull: −28.60 ‰ and great b-b gulls: −28.25 ‰, −26.65 ‰, −26.54 ‰, −26.47 ‰ from the same sampling site, Bilho, and one yellow-l. gull: −24.03 ‰). These values were unusually low compared to all other individuals (range, for all other samples from the Atlantic: [−24.90; −16.95] and for other yellow l. gulls from the Atlantic: [−19.37; −17.42]; Table S3), and could be explained by a different food source, particularly at the Bilho site (a sandbank inside the Loire estuary allowing the gulls to feed on freshwater and/or terrestrial prey). As the aim of the study was to identify the main drivers on a large scale, these values were excluded from the dataset. In addition, due to strong differences in isotopic baselines (Graham et al., 2010), data from the Atlantic and the Mediterranean coasts were analysed separately. The "Atlantic dataset" included three marine subregions (English Channel and North Sea, Celtic Sea and Bay of Biscay) and five seabird species (shags and four *Laridae* species: herring gulls, lesser b-b gulls, great b-b gulls and yellow-l. gulls). Two species (yellow-l. gull and shearwater) were sampled in the Mediterranean, and their datasets were analysed separately from each other ("Mediterranean yellow-l. gull dataset" and "shearwater dataset") because of non-overlapping of $\delta^{13}C$ values (range, yellow-l. gulls: [−19.64;-18.64] ‰ and shearwaters: [−24.8;-19.75] ‰, Table S3), due to strong differences in feeding habitat (coastal/terrestrial *vs.* oceanic, respectively, see Table S1).

$\delta^{13}C$ and $\delta^{15}N$ values were strongly and positively associated (Figs. S1 and S2) in the Atlantic dataset and in the Mediterranean yellow-l. gull dataset. Preliminary analyses showed that $\delta^{15}N$ values were a strong predictor of Hg concentrations in both datasets. We were also interested in the effect of feeding habitat ($\delta^{13}C$ values) on blood Hg concentrations but could not include $\delta^{13}C$ and $\delta^{15}N$ values in the same model because of their collinearity. We thus fitted a non-linear logistic model (nls with SSlogis function from "stats" package) with Hg concentrations as the response variable and $\delta^{15}N$ values as the explanatory variable (Fig. 2), and then extracted residuals from these nls models (named "Hg partial residuals" hereafter), to use them as the response variable in multifactorial regressions. Using partial residuals was an approach already applied to deal with collinearity between two predictors (*e.g.*, Bond and Diamond, 2009; Médieu et al., 2022; Ricca et al., 2008; Tartu et al., 2022). This approach enabled us to quantify the effects of site, feeding habitat ($\delta^{13}C$ values), and intrinsic factors (species and chick age, inferred from body mass) on the residual variation in Hg concentrations, after accounting for the effect of trophic position ($\delta^{15}N$ values).

Table 1
Model selection of linear mixed-effects models (LMEs) for the relationship between Hg partial residuals and extrinsic ($\delta^{13}C$ values and marine subregion) and intrinsic (chick mass and species) variables for the Atlantic dataset (including herring gull, lesser black-backed gull, great black-backed gull, yellow-legged gull, and European shag), based on Akaike's Information Criterion corrected for small sample sizes (AICc). Only the first ten models and the null model are presented (n_{total} = 20). The most parsimonious model is given in bold. K: number of parameters; ΔAICc: difference between the model with the smallest AICc-value and the model of interest; AIC*cwt*: Akaike's weight.

LMEs with site as a random factor and an exponential variance weight structure ($\delta^{13}C$ differed per species), n = 554									
Models	$\delta^{13}C$	Species	Mass	Marine subregion	$\delta^{13}C$:species	K	AICc	ΔAICc	AIC*cwt*
Mod1	X	X	X	X	X	20	350.9	0	0.387
Mod2	**X**	**X**		**X**	**X**	**19**	**350.9**	**0.06**	**0.376**
Mod3	X	X			X	17	353.1	2.29	0.123
Mod4	X	X	X		X	18	353.3	2.44	0.114
Mod5	X	X	X	X		16	574.6	223.76	0
Mod6	X	X		X		15	575.2	224.38	0
Mod 7	X		X	X		12	577.2	226.35	0
Mod 8	X	X	X			14	579	228.14	0
Mod 9	X	X				13	579.4	228.58	0
Mod 10	X		X			10	582.6	231.71	0
Null model						8	592.5	241.63	0

For the response "Hg partial residual", we built linear mixed-effects models (LMEs, package "MuMin", Bartoń, 2022), with site as a random variable for both the Atlantic and Mediterranean yellow-l. gull datasets. For the Atlantic dataset, mass (continuous variable) and $\delta^{13}C$ (continuous variable), species (categorical variable), marine subregions (categorical variable), and the $\delta^{13}C$-species interaction were the fixed explanatory variables. For the Mediterranean yellow-l. gull dataset, LMEs included only mass and $\delta^{13}C$ values as explanatory variables. For both datasets, continuous variables (mass and $\delta^{13}C$ variables) were scaled (mean = 0, SD = 1) to facilitate the comparison of effect sizes. In addition, to deal with residuals heteroscedasticity, exponential variance weights (package "nlme", Pinheiro et al., 2023) were added to the LMEs of both datasets (the exponential variance weight structure depended on $\delta^{13}C$ values and species in the Atlantic dataset, and only on $\delta^{13}C$ values for the Mediterranean yellow-l. gull dataset). For the Atlantic dataset, pairwise comparisons with post-hoc Tukey tests were performed to evaluate differences in Hg partial residuals between marine subregions and between species ("emmeans" package, Lenth et al., 2023).

In the shearwater dataset, $\delta^{13}C$ values were negatively correlated with $\delta^{15}N$ values (see details in Fig. S1), and Hg concentrations were not significantly associated to $\delta^{15}N$ values (Fig. 2). Therefore, LMEs were constructed with Hg concentration as the response variable, mass and $\delta^{13}C$ values as fixed effects, and site as a random effect. Mass and $\delta^{13}C$ values were scaled (mean = 0, SD = 1).

For all the models, body mass was used as a proxy of chick age, as shown in several seabird species (*e.g.*, Barrett, 1996; Lequette and Weimerskirch, 1990; Nelson, 1964); tarsus length was also tested as a proxy of chick age and led to the same results when used in regression models (data not shown).

For each initial model, the homoscedasticity and normal distribution of residuals were visually assessed (residuals *versus* fitted values, Q-Q graphs, Zuur et al., 2009). We performed model selection using the Akaike information criterion for small samples (AICc, "MuMin" package, Bartoń, 2022) to identify the best model(s). Explanatory variables included in the best model(s) were considered to have a significant effect, if the focal model performed better than the null model and other alternative models. If the difference in AICc values between two or more models (ΔAICc) was >2, the model with the lowest AICc was considered as the best. In contrast, if ΔAICc <2, models were considered of equal explanatory power. The explained deviance was calculated compared to the null model (Zuur et al., 2009). The relative importance of predictor variables was calculated by summing AICc*wt* (sum of weight, SW) of models including this variable. A significance level of $\alpha < 0.05$ was used for post-hoc Tukey tests. Result of LMEs were graphically presented using estimated marginal means with the "emmeans" package.

3. Results

3.1. Mercury concentrations in blood

Along the Atlantic coast, the lowest mean Hg concentrations were reported in herring gulls, while the highest were reported in great b-b

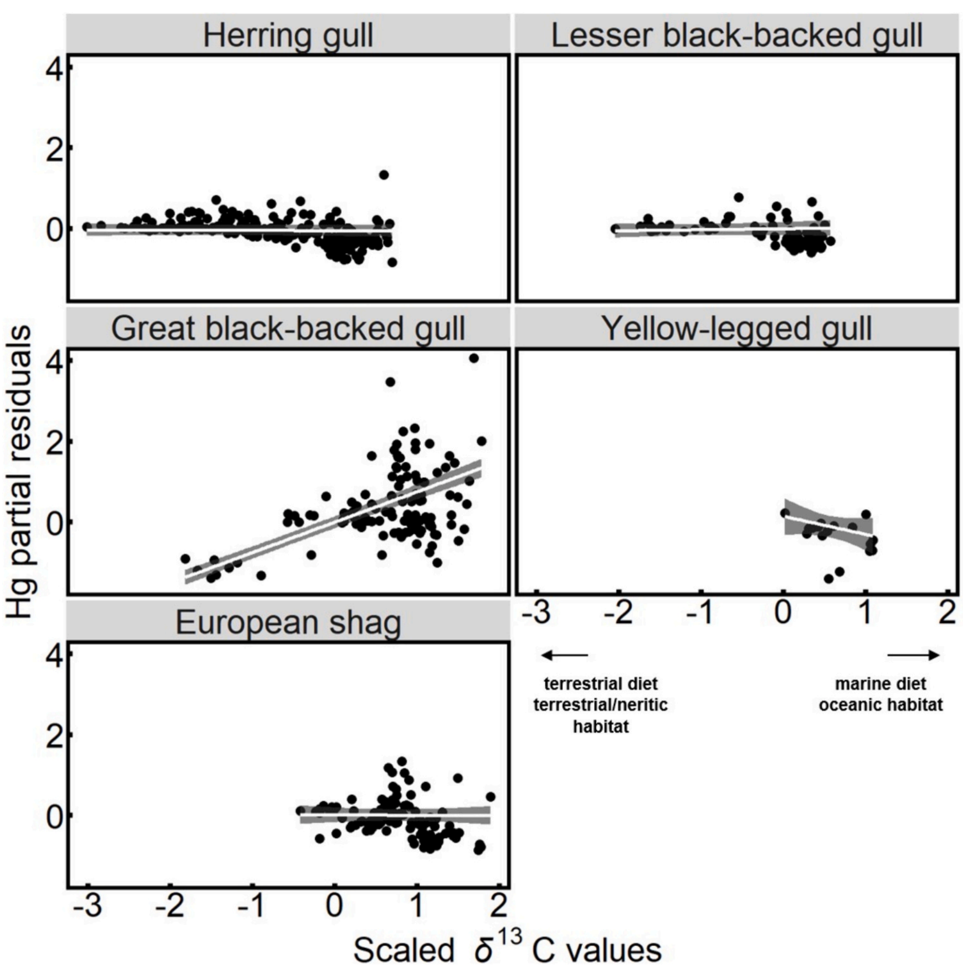

Fig. 3. Associations between Hg partial residuals and scaled $\delta^{13}C$ values in chicks of different seabird species from the French Atlantic coastline. The solid line represents the species-specific fitted models, and 95% confident interval is presented in grey. Six outliers were removed from the statistical analysis (see M&M).

gulls. In the English Channel and North Sea, mean blood Hg concentrations ranged from 0.33 ± 0.32 in herring gulls to 2.86 ± 0.85 μg g^{-1} dw in great b-b gulls. Similarly, Hg concentrations in the Celtic Sea ranged from 0.11 ± 0.05 in herring gulls to 2.86 ± 1.31 μg g^{-1} dw in great b-b gulls and in the Bay of Biscay from 0.27 ± 0.13 to 1.95 ± 0.58 μg g^{-1} dw in herring gulls and great b-b gulls, respectively. Finally, in the Mediterranean Sea, Hg concentrations ranged from 0.24 ± 0.13 in yellow-l. gulls to 2.99 ± 0.59 μg g^{-1} dw in shags. For each species, the mean (± SD), median and range of Hg concentrations, $\delta^{15}N$ and $\delta^{13}C$ values, for each sample site are presented in the SI (Tables S2, S3 and S4).

3.2. Extrinsic and intrinsic drivers of Hg concentrations

For the Atlantic dataset, ranges of partial Hg residuals were [−0.84;1.34] in herring gulls, [−0.59;0.77] for lesser b-b gulls, [−1.38;4.06] for great b-b gulls, [−1.41;0.22] for yellow-l. gulls and [−0.86;1.34] for shags. The best model explaining blood Hg partial residuals included all variables (scaled $\delta^{13}C$ values, species, and their interaction, and marine subregion), except mass, and explained 46% of the total variation (Table 1). Hg partial residuals were negatively associated with scaled $\delta^{13}C$ values, but the effect size was small (LME; estimate ± SE, −0.01 ± 0.02; $F_{1,525}$ = 35.42), and the association depended on species (post-hoc Tukey test, *p*-value <0.01, Table S5). Specifically, great b-b gulls had a positive association between Hg partial residuals and scaled $\delta^{13}C$ values (LME; 0.75 ± 0.04, Fig. 3), while other species had a weak negative association (small effect sizes; −0.44 ± 0.32 in yellow-l. gulls, −0.01 ± 0.74 in shags, −0.01 ± 0.02 in herring gulls and 0.03 ± 0.04 in lesser b-b gulls). Post-hoc comparisons of Hg partial residuals between species, and between marine subregions showed no significant differences (post-hoc Tukey tests, all *p*-values >0.05, Table S5, Fig. S3). For the Mediterranean yellow-l. gull dataset, $\delta^{13}C$ values were a significant predictor of Hg partial residuals with a weak positive association (LME; 0.07 ± 0.03; $F_{1,169}$ = 6.34, Fig. 4 and Table S6). For the shearwater dataset, models including scaled $\delta^{13}C$ values alone, or scaled $\delta^{13}C$ values and mass, and the null model all had similar explanatory power (ΔAICc <2; Table S6).

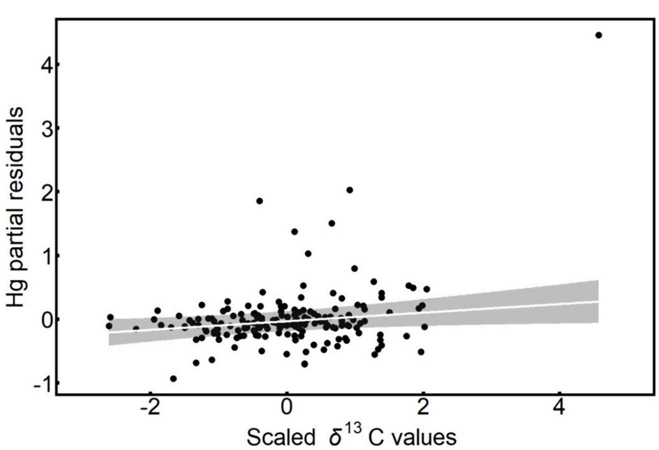

Fig. 4. Association between Hg partial residuals and scaled $\delta^{13}C$ values for yellow-legged gull chicks from the French Mediterranean region. The solid line represents the fitted model and 95% confident interval is presented in grey. β ± SE: slope 0.07 ± 0.03, intercept −0.03 ± 0.07, n = 180, linear mixed-effects model with site as a random factor, $\Delta AICc_{model\text{-}null}$: 4).

4. Discussion

This study is the first description of Hg concentrations in the blood of chicks of eight seabird species along the coast of metropolitan France. Our large scale, multi-site, and multi-species study showed no strong geographical difference in seabird Hg contamination among Atlantic marine subregions (English Channel and North Sea, Celtic Sea and Bay of Biscay), nor between the Atlantic and Mediterranean coasts. Trophic ecology (feeding habitat and trophic position inferred from $\delta^{13}C$ and $\delta^{15}N$ values) was identified as the main driver of variation in Hg concentrations, which were higher in species feeding in marine habitats at higher trophic positions.

4.1. Mercury concentrations in blood: comparison among seabirds

Hg concentrations were consistent with values previously reported in seabird chicks in metropolitan France (Bay of the Seine River, Chausey Islands, Isle of Ré, Binkowski et al., 2021; Jouanneau et al., 2022; Table S7). However, Hg concentrations in herring gulls from the Chausey Islands were higher than those reported in 2015–2018 (Binkowski et al., 2021), while isotopic values (mean ± SD: $\delta^{13}C$: −20.60 ± 1.22 ‰ and $\delta^{15}N$: 11.74 ± 1.56 ‰) were comparable, suggesting that other factors might explain the higher Hg concentrations reported here (Tables S3 and S7). Mean Hg concentrations were overall within the range of those documented previously in chicks of other seabird species and sites (*e.g.*, Southern Ocean, Western Atlantic Ocean, Pacific Ocean; Table S7). Herring gulls, yellow-l. gulls and kittiwakes showed the lowest concentrations in our dataset (<0.5 μg g^{-1} dw) and were comparable to those of other gull species from the Western Atlantic Ocean or Pacific Ocean (Table S5; Goodale et al., 2008; Peterson et al., 2017; Sebastiano et al., 2017). Lesser b-b gulls and shearwaters had intermediate Hg concentrations (~0.6 μg g^{-1} dw), within the same range as south polar skua chicks *Catharacta maccormicki* and penguin chicks *Pygoscelis* sp. (Antarctica, Carravieri et al., 2017; Souza et al., 2020). Scopoli's shearwaters had Hg concentrations comparable to chicks of the same species from Malta, in the southern eastern Mediterranean (0.6 to 1.0 μg g^{-1} dw, Costantini et al., 2020). Shags, gannets and great b-b gulls had the highest concentrations (mostly >1 μg g^{-1} dw), comparable to seabird chicks from French Guiana (magnificent frigatebirds *Fregata magnificens*), Canada (Glaucous gulls *Larus hyperboreus*), USA (Forster's terns *Sterna forsteri*), Crozet Islands (brown skuas *Catharacta skua lönnbergi*) and Kerguelen Islands (white-chinned petrels *Procellaria aequinoctialis*) (Burnham et al., 2018; Carravieri et al., 2020, 2017; Eagles-Smith et al., 2008; Sebastiano et al., 2016).

At the individual level, some birds had relatively high Hg concentrations, while their isotopic values were within the same range of other individuals. This suggests potential point contamination of the food supplied to the chicks. In particular, one yellow-l. gull chick (5.46 μg g^{-1} dw) had Hg concentrations comparable to the adults (mean adult yellow-l. gulls: 6.00 ± 2.72 μg g^{-1} dw, Jouanneau et al., 2022) and one great b-b gull chick (6.2 μg g^{-1} dw) had a concentration higher than the maximum Hg concentration currently reported in the blood of seabird chicks (brown skua: 5.8 μg g^{-1} dw in Carravieri et al., 2017).

4.2. Intrinsic and extrinsic drivers of Hg concentrations

4.2.1. Mercury and feeding ecology

Variation in Hg concentrations at individual, species and community levels in seabirds is often driven by trophic ecology (*e.g.*, Ackerman et al., 2016; Binkowski et al., 2021; Carravieri et al., 2020; Chételat et al., 2020; Jouanneau et al., 2022; Sebastiano et al., 2017; Wiener et al., 2003). Blood Hg concentrations and $\delta^{15}N$ values were strongly associated in the Atlantic seabird community, consistent with the biomagnification of Hg along food webs (Lavoie et al., 2010). Species with a higher trophic position (discriminated with $\Delta\delta^{15}N$ calculated between species >3.4, as described by Hobson et al., 1994; Tables S3–S4–S8) had higher Hg concentrations (great b-b gull) than species at lower trophic positions (herring gull). This positive association has already been reported in the blood of chicks from subtropical and Arctic avian communities (Burnham et al., 2018; Sebastiano et al., 2017), and in *Laridae* colonies in France (Binkowski et al., 2021; Jouanneau et al., 2022). For the Mediterranean region, a similar Hg-δ^{15}N trend was observed between individuals of yellow-l. gulls, as previously reported for chicks of other Mediterranean gull species (Audouin's gull *Larus audouinii*, Sanpera et al., 2007). No relationship between Hg concentrations and δ^{15}N values was observed in shearwaters, contrary to previous results for the same species (Costantini et al., 2020). This could be linked to the smaller range of Hg concentrations in the shearwaters of our study (0.10–1.17 μg g^{-1} dw) compared to Costantini et al. (2020) (0.23–4.29 μg g^{-1} dw).

Feeding habitat (marine *vs.* terrestrial/neritic or pelagic *vs.* benthic, inferred from δ^{13}C values) has previously been identified as a driver of Hg contamination in seabirds from different communities (Binkowski et al., 2021; Burnham et al., 2018; Carravieri et al., 2020; Chételat et al., 2020). Here, piscivorous specialists (shags) and opportunistic generalists (herring gulls, lesser b-b gulls and yellow-l. gulls) using neritic and/or terrestrial habitats all showed a weak negative association between Hg partial residuals and δ^{13}C values. The small effect sizes of these associations challenge their biological meaning. In contrast, great b-b gulls showed a strong positive relationship between Hg partial residuals and δ^{13}C values, as previously shown in chicks from an Arctic seabird community (Bond and Diamond, 2009) or between Hg and δ^{13}C values in gulls in France (Seine estuary, English Channel coast, Binkowski et al., 2021; Isle of Ré, Atlantic coast, Jouanneau et al., 2022). Species relying on marine resources have been shown to have higher Hg concentrations than species associated with terrestrial or coastal resources (Ackerman et al., 2016; Ochoa-acuña et al., 2002; Thorne et al., 2021). This unexpected positive Hg−δ^{13}C association (after accounting for δ^{15}N) for great b-b gulls compared to the overall model could be explained by high between-individual variation in feeding strategies of great b-b gulls and an overrepresentation of terrestrial/coastal species (shags, herring gulls, lesser b-b gulls and yellow-l. gulls) compared to coastal/oceanic species (great b-b gulls), which limits our power to quantify relationships in oceanic habitats. In contrast to other gulls, the diet of great b-b gulls relies mainly on marine resources (Binkowski et al., 2021; Jouanneau et al., 2022). Unlike coastal and benthic feeders such as shags, great b-b gulls have a more opportunistic and diverse array of marine prey with potentially variable Hg content, which may lead to greater variability in Hg concentrations.

Yellow-l. gulls showed between-region differences in the association of Hg partial residuals and δ^{13}C values, with a negative and a positive correlation for the Atlantic and Mediterranean regions, respectively. However, the effect size of both relationships was small and the limited sample size in the Atlantic ($n = 20$) compared with the Mediterranean ($n = 195$) could drive divergent trends. Moreover, yellow-l. gulls from the Mediterranean Sea showed a larger variation in δ^{13}C values (coefficient of variation: Atlantic: 2.7% and Mediterranean: 7.5%) that could suggest differences in the use of marine resources depending on the region. In the Mediterranean, yellow-l. gull is reported as a generalist species with varying individual specialization in feeding habitat (*e.g.*, diverse marine resources, urban prey, garbage and agriculture habitats) (Navarro et al., 2017; Ramos et al., 2009). These between- and within-species variations are representative of the complexity of the relationship between Hg contamination and feeding habitat (inferred from δ^{13}C values).

Shearwaters use only oceanic feeding habitats, resulting in a restricted trophic niche (Afán et al., 2014) with little isotopic variation. Accordingly, δ^{13}C values and Hg concentrations were not correlated, as previously shown in the Mediterranean for this species (Costantini et al., 2020). Using δ^{13}C values as a spatial proxy in species specialised in a single feeding habitat may be insufficient to establish the relationship between Hg concentrations and feeding habitat.

4.2.2. Mercury and spatial variability

There was no clear spatial association of Hg concentrations with marine subregions on the Atlantic coast, with each species presenting a distinct pattern (Fig. S3). For the two species with widespread sampling, herring gulls had Hg means ranging from 0.11 μg g^{-1} dw at the Sept-Iles (Celtic Sea) to 1.74 μg g^{-1} dw at Isle of Ré (Bay of Biscay), whereas great b-b gulls had their lowest mean Hg concentration of 1.13 μg g^{-1} dw at Houat-Hoëdic (Bay of Biscay) and their highest concentrations of 2.86 μg g^{-1} dw at Chausey and Brest (Celtic Sea) (Table S2). For species breeding on Atlantic and Mediterranean sites, such as yellow-l. gulls, Hg contamination was homogeneous, except for a few sites with high Hg concentrations (Isle of Ré – Bay of Biscay, the Western French Mediterranean coast, and Bonifacio – Southern Corsica; Table S2). Similarly, shags showed large site-specific variation in Hg burdens with concentrations three times higher in Bonifacio (2.99 μg g^{-1} dw at Bonifacio – Mediterranean Sea) than in the Atlantic (ranging from 0.71 to 1.12 μg g^{-1} dw at the Glenan Islands and Houat-Hoëdic – Bay of Biscay, respectively; Table S2). These "hotspots" of Hg contamination along the French Atlantic and Mediterranean coasts are consistent with results in lower trophic position species (Briant et al., 2017; Cresson et al., 2015). Specifically, Hg concentrations in bivalves and fish were high close to estuarine sites on the Atlantic coasts (*i.e.*, Seine, Loire and Gironde estuaries, Briant et al., 2017) and higher on the Eastern Mediterranean coast (especially Southern Corsica) than the Western Mediterranean coasts (Briant et al., 2017; Cresson et al., 2015). Hg bioavailability is the result of complex local biogeochemical, hydrological, and topographical variabilities, which are then transferred along the food web (Driscoll et al., 2013; Kotnik et al., 2007; Mason et al., 2012; Ullrich et al., 2001). Specifically, oligotrophy was previously reported to be a main driver of Hg bioaccumulation (Chouvelon et al., 2018). Aquatic organisms of oligotrophic waters concentrate more Hg than in other types of waters, because Hg methylation rate is more efficient inducing higher Hg bioavailability, as well as a bioconcentration accentuated by the low productivity of the ecosystem, with a lower dilution of Hg among phytoplanktonic cells (Heimbürger et al., 2010; Pickhardt et al., 2002). The "Mediterranean Mercury Anomaly", driven by oligotrophy and other factors, results in higher Hg concentrations in different taxa (crustaceans, sharks, and fish) in Mediterranean compared to Atlantic waters (Chouvelon et al., 2018; Cresson et al., 2015). However, spatial comparisons need to be considered with caution as isotopic baselines also largely differ among these zones (Chouvelon et al., 2018). Anthropogenic activities are thought to contribute to high local Hg contamination in biota inducing "hotspots" associated with proximity to cities, industrialized ports and large continental fluvial inputs (Binkowski et al., 2021; Briant et al., 2017; Cresson et al., 2015; Pereira et al., 2019). Overall, blood Hg contamination in the seabirds studied here was spatially uniform along the French coast, with only isolated sites presenting high concentrations, probably because of local geological characteristics and/or anthropogenic activities.

4.2.3. Mercury and intrinsic factors: mass and taxonomy

Age is an essential factor to consider when investigating chick exposure, as Hg bioavailability varies quadratically from hatching to the post-fledging phase (Ackerman et al., 2011). After hatching, Hg from maternal transfer and food intake is diluted by mass gain and deposited into down and later feathers (Wenzel et al., 1996). Progressively, growth and feather development cannot compensate dietary Hg intake, and blood Hg concentrations increase again (Ackerman et al., 2011). Here, body mass was used as a proxy of chick age (body mass and chick age are highly correlated in seabirds; Barrett, 1996; Lequette and Weimerskirch, 1990; Nelson, 1964), but was not a good predictor of variation in blood Hg (after accounting for δ^{15}N), likely because all chicks were sampled after the dilution phase, when trophic ecology plays a prominent role in Hg concentration variation.

Interspecific differences in Hg concentrations (raw or corrected for δ^{15}N) were observed within the same taxonomic groups, such as the

Larus genus with lower concentrations in herring gulls and yellow-l. gulls than in lesser b-b gulls or great b-b gulls. Compared with trophic ecology, taxonomy seems to play a minor role in interspecific differences in blood Hg concentrations, as previously reported in other seabirds at the levels of genus, family, and order (Anderson et al., 2009; Carravieri et al., 2014c).

4.3. Potential health risk of Hg for French seabirds

Based on Hg toxicity benchmarks established for whole blood of adults (Ackerman et al., 2016), most chicks (74%, $n_{no\ risk} = 623$, $n_{total} = 843$) were classified at no risk category (<0.95 μg g^{-1} dw, converted from 0.2 μg g^{-1} ww with moisture percentage of 79%, Eagles-Smith et al., 2008; Fig. 5) whereas 26% ($n_{low\ risk} = 216$) were classified at low

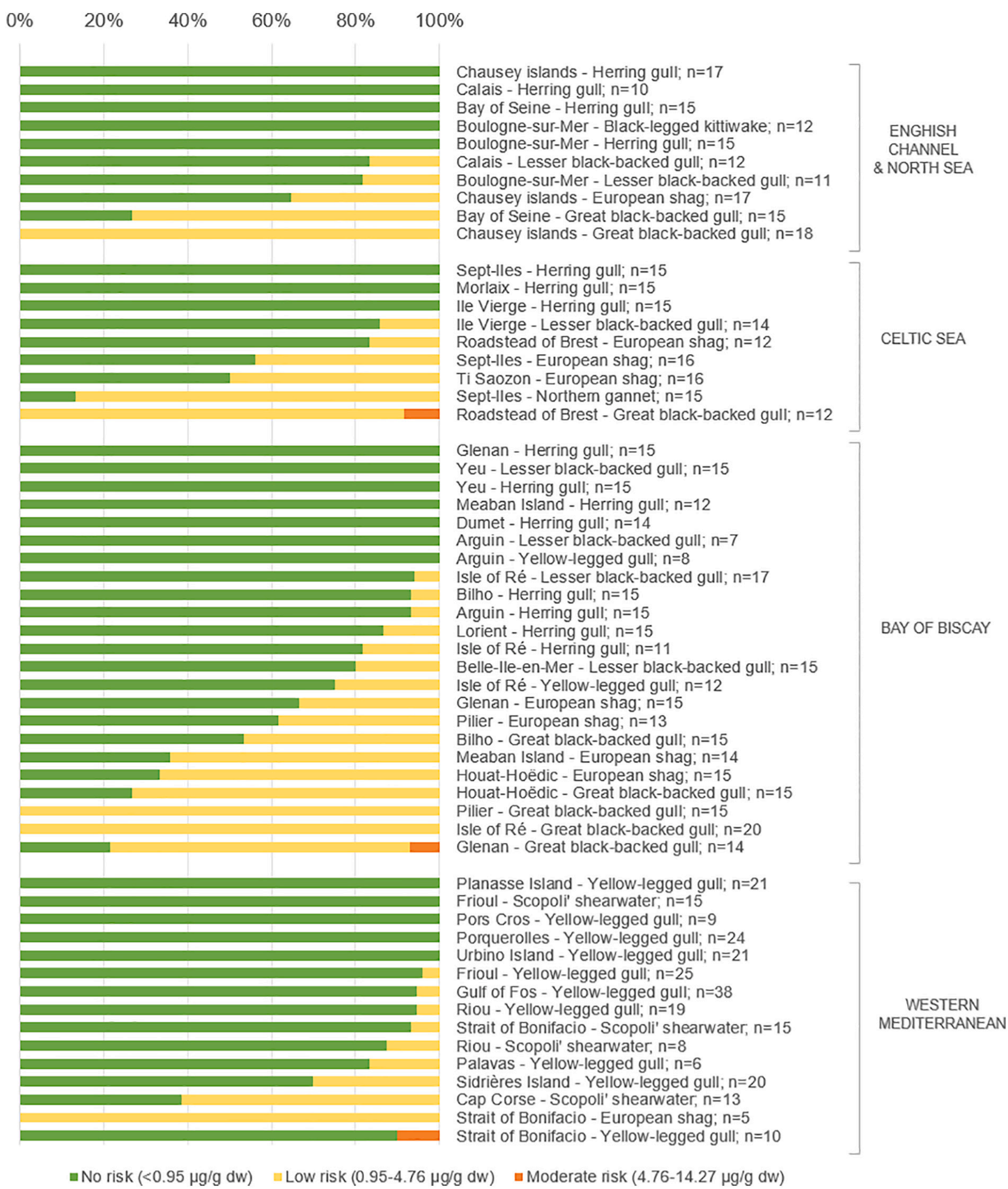

Fig. 5. Overview of the percentage of individual seabird chicks per site along the French coasts, that are at risk for Hg toxicity according to thresholds established for adults (Ackerman et al., 2016, converted to dry weight with moisture percentage of 79%, Eagles-Smith et al., 2008). Thresholds are classified into three categories: <0.95 μg g^{-1} dw (green; below known effect levels), 0.95–4.76 μg g^{-1} dw (yellow; low risk) and 4.76–14.27 μg g^{-1} dw (orange; moderate risk). Brackets indicate marine subregions.

risk (0.95–4.76 μg g^{-1} dw, converted) and only three individuals (<0.5% of chicks) at moderate risk (4.76–14.27 μg g^{-1} dw converted). However, chicks may differ from adults in their susceptibility to Hg, particularly during the growth phase, which corresponds to the development of the nervous system. Importantly, sublethal effects have been reported even at concentrations considered at no risk in chicks of lesser b-b gulls (~0.25 μg g^{-1} dw, Santos et al., 2020) and shearwaters (0.6 to 1.0 μg g^{-1} dw, Costantini et al., 2020). Santos et al. (2020) showed changes in energy metabolism (decrease of total proteins, carbohydrates, and lipids in blood), as well as an increase in oxidative stress in chicks of lesser b-b gulls at ~0.25 μg g^{-1} dw. In our study, 77% of individuals ($n = 651$) exceeded this level. Moreover, Hg concentrations (0.6 to 1.0 μg g^{-1} dw) were also associated with high oxidative stress in chicks of shearwaters (Costantini et al., 2020). Exposure to Hg may raise ecotoxicological concerns, but Hg can be detoxified by selenium (Se), a trace element that plays a protective role against Hg toxicity (Ikemoto et al., 2004; Kim et al., 1996). Additional studies on Se could help evaluate whether species and geographical variability in this element could compensate Hg contamination (Cruz-Flores et al., 2024). Further studies are also now required to better understand the consequences of Hg contamination, particularly during the developmental stages, but also on lifetime fitness.

5. Conclusions

Our study provides novel information on Hg contamination in seabirds from metropolitan France and describes its main drivers for a large panel of seabird species with various trophic ecologies. Hg variation was explained mainly by extrinsic trophic drivers. Trophic position was a key contributor, with higher δ^{15}N values resulting in higher blood Hg concentrations. Chicks from species with diverse trophic ecologies appear to be good bioindicators of Hg transfer to predators in coastal ecosystems. We also provided a unique large-scale description of Hg burdens in seabird chicks, which points to geographically homogeneous variation in Hg contamination along the French coasts. Even if most chicks were classified to be at low risk according to adult thresholds, concentrations in excess of sublethal effects were found, calling for future studies on the effects of Hg on early life stages.

CRediT authorship contribution statement

Prescillia Lemesle: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Alice Carravieri:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Gauthier Poiriez:** Project administration, Investigation. **Romain Batard:** Investigation. **Aurélie Blanck:** Resources, Investigation. **Armel Deniau:** Investigation. **Gilles Faggio:** Investigation. **Jérôme Fort:** Writing – review & editing, Resources. **Fabrice Gallien:** Investigation. **William Jouanneau:** Writing – review & editing, Investigation. **Gilles le Guillou:** Investigation. **Carole Leray:** Investigation. **Karen D. McCoy:** Writing – review & editing, Resources, Funding acquisition. **Pascal Provost:** Investigation. **Marie-Catherine Santoni:** Investigation. **Manrico Sebastiano:** Writing – review & editing, Investigation. **Alain Ward:** Investigation. **Olivier Chastel:** Writing – review & editing, Supervision, Resources, Investigation. **Paco Bustamante:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175857.

References

Ackerman, J.T., Eagles-Smith, C.A., Herzog, M.P., 2011. Bird mercury concentrations change rapidly as chicks age: toxicological risk is highest at hatching and fledging. Environ. Sci. Technol. 45, 5418–5425. https://doi.org/10.1021/es200647g.

Ackerman, J.T., Eagles-Smith, C.A., Herzog, M.P., Hartman, C.A., Peterson, S.H., Evers, D.C., Jackson, A.K., Elliott, J.E., Vander Pol, S.S., Bryan, C.E., 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.

Ackerman, J.T., Herzog, M.P., Evers, D.C., Cristol, D.A., Kenow, K.P., Heinz, G.H., Lavoie, R.A., Brasso, R.L., Mallory, M.L., Provencher, J.F., Braune, B.M., Matz, A., Schmutz, J.A., Eagles-Smith, C.A., Savoy, L.J., Meyer, M.W., Hartman, C.A., 2020. Synthesis of maternal transfer of mercury in birds: implications for altered toxicity risk. Environ. Sci. Technol. 54, 2878–2891. https://doi.org/10.1021/acs.est.9b06119.

Afán, I., Navarro, J., Cardador, L., Ramírez, F., Kato, A., Rodríguez, B., Ropert-Coudert, Y., Forero, M.G., 2014. Foraging movements and habitat niche of two closely related seabirds breeding in sympatry. Mar. Biol. 161, 657–668. https://doi.org/10.1007/s00227-013-2368-4.

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

Albertos, S., Berenguer, N.I., Sánchez-Virosta, P., Gómez-Ramírez, P., Jiménez, P., Torres-Chaparro, M.Y., Valverde, I., Navas, I., María-Mojica, P., García-Fernández, A.J., Espín, S., 2020. Mercury exposure in birds linked to marine ecosystems in the Western Mediterranean. Arch. Environ. Contam. Toxicol. 79, 435–453. https://doi.org/10.1007/s00244-020-00768-1.

Anderson, O., Phillips, R., McDonald, R., Shore, R., McGill, R., Bearhop, S., 2009. Influence of trophic position and foraging range on mercury levels within a seabird community. Mar. Ecol. Prog. Ser. 375, 277–288. https://doi.org/10.3354/meps07784.

Barrett, R.T., 1996. Egg laying, chick growth and food of kittiwakes Rissa tridactyla at Hopen. Svalbard. Polar Res. 15, 107–113.

Bartoń, K., 2022. MuMin: Multi-Model Inference. R package version 1.47.1. https://CRAN.R-project.org/package=MuMIn.

Bearhop, S., Thompson, D.R., Waldron, S., Russell, I.C., Alexander, G., Furness, R.W., 1999. Stable isotopes indicate the extent of freshwater feeding by cormorants Phalacrocorax carbo shot at inland fisheries in England. J. Appl. Ecol. 36, 75–84.

Bearhop, S., Ruxton, G.D., Furness, R.W., 2000. Dynamics of mercury in blood and feathers of great skuas. Environ. Toxicol. Chem. 19, 1638–1643. https://doi.org/10.1002/etc.5620190622.

Bearhop, S., Waldron, S., Votier, S.C., Furness, R.W., 2002. Factors that influence assimilation rates and fractionation of nitrogen and carbon stable isotopes in avian blood and feathers. Physiol. Biochem. Zool. 75, 451–458. https://doi.org/10.1086/342800.

Binkowski, L.J., Fort, J., Brault-Favrou, M., Gallien, F., Le Guillou, G., Chastel, O., Bustamante, P., 2021. Foraging ecology drives mercury contamination in chick gulls from the English Channel. Chemosphere 267, 128622. https://doi.org/10.1016/j.chemosphere.2020.128622.

Blévin, P., Carravieri, A., Jaeger, A., Chastel, O., Bustamante, P., Cherel, Y., 2013. Wide range of mercury contamination in chicks of Southern Ocean seabirds. PLoS One 8, e54508. https://doi.org/10.1371/journal.pone.0054508.

Bond, A.L., Diamond, A.W., 2009. Mercury concentrations in seabird tissues from Machias Seal Island, New Brunswick. Canada. Sci. Total Environ. 407, 4340–4347. https://doi.org/10.1016/j.scitotenv.2009.04.018.

Bond, A.L., Jones, I.L., 2009. A practical introduction to stable-isotope analysis for seabird biologists: approaches, cautions and caveats. Mar. Ornithol. 37, 183–188.

Bond, A.L., Robertson, G.J., 2015. Mercury concentrations in multiple tissues of Arctic Iceland Gulls (*Larus glaucoides*) wintering in Newfoundland. Arct. Sci. 1, 1–8. https://doi.org/10.1139/as-2015-0004.

Briant, N., Chouvelon, T., Martinez, L., Brach-Papa, C., Chiffoleau, J., Savoye, N., Sonke, J., Knoery, J., 2017. Spatial and temporal distribution of mercury and methylmercury in bivalves from the French coastline. Mar. Pollut. Bull. 114, 1096–1102. https://doi.org/10.1016/j.marpolbul.2016.10.018.

Burger, J., Gochfeld, M., 2004. Marine birds as sentinels of environmental pollution. EcoHealth 1. https://doi.org/10.1007/s10393-004-0096-4.

Burnham, J.H., Burnham, K.K., Chumchal, M.M., Welker, J.M., Johnson, J.A., 2018. Correspondence between mercury and stable isotopes in high Arctic marine and terrestrial avian species from northwest Greenland. Polar Biol. 41, 1475–1491. https://doi.org/10.1007/s00300-018-2302-9.

Bustamante, P., Le Verge, T., Bost, C.-A., Brault-Favrou, M., Le Corre, M., Weimerskirch, H., Cherel, Y., 2023. Mercury contamination in the tropical seabird community from Clipperton Island, eastern Pacific Ocean. Ecotoxicology. https://doi.org/10.1007/s10646-023-02691-2.

Carravieri, A., Bustamante, P., Churlaud, C., Fromant, A., Cherel, Y., 2014a. Moulting patterns drive within-individual variations of stable isotopes and mercury in seabird body feathers: implications for monitoring of the marine environment. Mar. Biol. 161, 963–968. https://doi.org/10.1007/s00227-014-2394-x.

Carravieri, A., Bustamante, P., Tartu, S., Meillère, A., Labadie, P., Budzinski, H., Peluhet, L., Barbraud, C., Weimerskirch, H., Chastel, O., Cherel, Y., 2014b. Wandering albatrosses document latitudinal variations in the transfer of persistent organic pollutants and mercury to Southern Ocean predators. Environ. Sci. Technol. 48, 14746–14755. https://doi.org/10.1021/es504601m.

Carravieri, A., Cherel, Y., Blévin, P., Brault-Favrou, M., Chastel, O., Bustamante, P., 2014c. Mercury exposure in a large subantarctic avian community. Environ. Pollut. 190, 51–57. https://doi.org/10.1016/j.envpol.2014.03.017.

Carravieri, A., Cherel, Y., Brault-Favrou, M., Churlaud, C., Peluhet, L., Labadie, P., Budzinski, H., Chastel, O., Bustamante, P., 2017. From Antarctica to the subtropics: contrasted geographical concentrations of selenium, mercury, and persistent organic pollutants in skua chicks (Catharacta spp.). Environ. Pollut. 228, 464–473. https://doi.org/10.1016/j.envpol.2017.05.053.

Carravieri, A., Fort, J., Tarroux, A., Cherel, Y., Love, O.P., Prieur, S., Brault-Favrou, M., Bustamante, P., Descamps, S., 2018. Mercury exposure and short-term consequences on physiology and reproduction in Antarctic petrels. Environ. Pollut. 237 https://doi.org/10.1016/j.envpol.2017.11.004.

Carravieri, A., Bustamante, P., Labadie, P., Budzinski, H., Chastel, O., Cherel, Y., 2020. Trace elements and persistent organic pollutants in chicks of 13 seabird species from Antarctica to the subtropics. Environ. Int. 134, 105225 https://doi.org/10.1016/j.envint.2019.105225.

Carravieri, A., Lorioux, S., Angelier, F., Chastel, O., Albert, C., Bråthen, V.S., Brisson-Curadeau, É., Clairbaux, M., Delord, K., Giraudeau, M., Perret, S., Poupart, T., Ribout, C., Viricel-Pante, A., Grémillet, D., Bustamante, P., Fort, J., 2023. Carryover effects of winter mercury contamination on summer concentrations and reproductive performance in little auks. Environ. Pollut. 318, 120774 https://doi.org/10.1016/j.envpol.2022.120774.

Chastel, O., Fort, J., Ackerman, J.T., Albert, C., Angelier, F., Basu, N., Blévin, P., Brault-Favrou, M., Bustnes, J.O., Bustamante, P., Danielsen, J., Descamps, S., Dietz, R., Erikstad, K.E., Eulaers, I., Ezhov, A., Fleishman, A.B., Gabrielsen, G.W., Gavrilo, M., Gilchrist, G., Gilg, O., Gíslason, S., Golubova, E., Goutte, A., Grémillet, D., Hallgrimsson, G.T., Hansen, E.S., Hanssen, S.A., Hatch, S., Huffeldt, N.P., Jakubas, D., Jónsson, J.E., Kitaysky, A.S., Kolbeinsson, Y., Krasnov, Y., Letcher, R.J., Linnebjerg, J.F., Mallory, M., Merkel, F.R., Moe, B., Montevecchi, W.J., Mosbech, A., Olsen, B., Orben, R.A., Provencher, J.F., Ragnarsdottir, S.B., Reiertsen, T.K., Rojek, N., Romano, M., Søndergaard, J., Strøm, H., Takahashi, A., Tartu, S., Thórarinsson, T.L., Thiebot, J.-B., Will, A.P., Wilson, S., Wojczulanis-Jakubas, K., Yannic, G., 2022. Mercury contamination and potential health risks to Arctic seabirds and shorebirds. Sci. Total Environ. 844, 156944 https://doi.org/10.1016/j.scitotenv.2022.156944.

Cherel, Y., Barbraud, C., Lahournat, M., Jaeger, A., Jaquemet, S., Wanless, R.M., Phillips, R.A., Thompson, D.R., Bustamante, P., 2018. Accumulate or eliminate? Seasonal mercury dynamics in albatrosses, the most contaminated family of birds. Environ. Pollut. 241, 124–135. https://doi.org/10.1016/j.envpol.2018.05.048.

Chételat, J., Ackerman, J.T., Eagles-Smith, C.A., Hebert, C.E., 2020. Methylmercury exposure in wildlife: a review of the ecological and physiological processes affecting contaminant concentrations and their interpretation. Sci. Total Environ. 711, 135117 https://doi.org/10.1016/j.scitotenv.2019.135117.

Chouvelon, T., Cresson, P., Bouchoucha, M., Brach-Papa, C., Bustamante, P., Crochet, S., Marco-Miralles, F., Thomas, B., Knoery, J., 2018. Oligotrophy as a major driver of mercury bioaccumulation in medium-to high-trophic level consumers: a marine ecosystem-comparative study. Environ. Pollut. 233, 844–854. https://doi.org/10.1016/j.envpol.2017.11.015.

Claisse, D., Cossa, D., Bretaudeau-Sanjuan, J., Touchard, G., Bombled, B., 2001. Methylmercury in molluscs along the French coast. Mar. Pollut. Bull. 42, 329–332. https://doi.org/10.1016/S0025-326X(01)00036-4.

Costantini, D., Bustamante, P., Brault-Favrou, M., Dell`Omo, G., 2020. Patterns of mercury exposure and relationships with isotopes and markers of oxidative status in chicks of a Mediterranean seabird. Environ. Pollut. 260, 114095 https://doi.org/10.1016/j.envpol.2020.114095.

Cresson, P., Bouchoucha, M., Miralles, F., Elleboode, R., Mahé, K., Marusczak, N., Thebault, H., Cossa, D., 2015. Are red mullet efficient as bio-indicators of mercury contamination? A case study from the French Mediterranean. Mar. Pollut. Bull. 91, 191–199. https://doi.org/10.1016/j.marpolbul.2014.12.005.

Cruz-Flores, M., Lemaire, J., Brault-Favrou, M., Christensen-Dalsgaard, S., Churlaud, C., Descamps, S., Elliott, K., Erikstad, K.E., Ezhov, A., Gavrilo, M., Grémillet, D., Guillou, G., Hatch, S., Per Huffeldt, N., Kitaysky, A.S., Kolbeinsson, Y., Krasnov, Y., Langset, M., Leclaire, S., Linnebjerg, J.F., Lorentzen, E., Mallory, M.L., Merkel, F.R., Montevecchi, W., Mosbech, A., Patterson, A., Perret, S., Provencher, J.F., Reiertsen, T.K., Renner, H., Strøm, H., Takahashi, A., Thiebot, J.-B., Thórarinsson, T. L., Will, A., Bustamante, P., Fort, J., 2024. Spatial distribution of selenium-mercury in Arctic seabirds. Environ. Pollut. 343, 123110 https://doi.org/10.1016/j.envpol.2023.123110.

Driscoll, C.T., Mason, R.P., Chan, H.M., Jacob, D.J., Pirrone, N., 2013. Mercury as a global pollutant: sources, pathways, and effects. Environ. Sci. Technol. 47, 4967–4983. https://doi.org/10.1021/es305071v.

Eagles-Smith, C.A., Ackerman, J.T., Adelsbach, T.L., Takekawa, J.Y., Miles, A.K., Keister, R.A., 2008. Mercury correlations aming six tissues for four waterbird species breeding in San Francisco Bay, California, USA. Environ. Toxicol. Chem. 27, 2136. https://doi.org/10.1897/08-038.1.

Eagles-Smith, C.A., Ackerman, J.T., Yee, J., Adelsbach, T.L., 2009. Mercury demethylation in waterbird livers: dose–response thresholds and differences among species. Environ. Toxicol. Chem. 28, 568–577. https://doi.org/10.1897/08-245.1.

Elliott, J.E., Elliott, K.H., 2013. Tracking marine pollution. Science 340, 556–558. https://doi.org/10.1126/science.1235197.

Evers, D.C., Ackerman, J.T., Åkerblom, S., Bally, D., Basu, N., Bishop, K., Bodin, N., Braaten, H.F.V., Burton, M.E.H., Bustamante, P., Chen, C., Chételat, J., Christian, L., Dietz, R., Drevnick, P., Eagles-Smith, C., Fernandez, L.E., Hammerschlag, N., Harmelin-Vivien, M., Harte, A., Krümmel, E.M., Brito, J.L., Medina, G., Barrios Rodriguez, C.A., Stenhouse, I., Sunderland, E., Takeuchi, A., Tear, T., Vega, C., Wilson, S., Wu, P., 2024. Global mercury concentrations in biota: their use as a basis for a global biomonitoring framework. Ecotoxicology. https://doi.org/10.1007/s10646-024-02747-x.

GISOM, 2023. Recensement national des oiseaux marins nicheurs en France hexagonale: Enquête 2020-2022. GROUPEMENT D'INTÉRÊT SCIENTIFIQUE OISEAUX MARINS, p. 61 (accessed 14.10.23).
Goodale, M.W., Evers, D.C., Mierzykowski, S.E., Bond, A.L., Burgess, N.M., Otorowski, C. I., Welch, L.J., Hall, C.S., Ellis, J.C., Allen, R.B., Diamond, A.W., Kress, S.W., Taylor, R.J., 2008. Marine foraging birds as bioindicators of mercury in the Gulf of Maine. EcoHealth 5, 409–425. https://doi.org/10.1007/s10393-009-0211-7.
Goutner, V., Becker, P.H., Liordos, V., 2013. Low mercury contamination in Mediterranean gull Larus melanocephalus chicks in Greece. Chem. Ecol. 29, 1–10. https://doi.org/10.1080/02757540.2012.744828.
Goutte, A., Barbraud, C., Meillère, A., Carravieri, A., Bustamante, P., Labadie, P., Budzinski, H., Delord, K., Cherel, Y., Weimerskirch, H., Chastel, O., 2014a. Demographic consequences of heavy metals and persistent organic pollutants in a vulnerable long-lived bird, the wandering albatross. Proc. R. Soc. B Biol. Sci. 281, 20133313 https://doi.org/10.1098/rspb.2013.3313.
Goutte, A., Bustamante, P., Barbraud, C., Delord, K., Weimerskirch, H., Chastel, O., 2014b. Demographic responses to mercury exposure in two closely related Antarctic top predators. Ecology 95, 1075–1086. https://doi.org/10.1890/13-1229.1.
Graham, B.S., Koch, P.L., Newsome, S.D., McMahon, K.W., Aurioles, D., 2010. Using isoscapes to trace the movements and foraging behavior of top predators in oceanic ecosystems. In: West, J.B., Bowen, G.J., Dawson, T.E., Tu, K.P. (Eds.), Isoscapes. Springer Netherlands, Dordrecht, pp. 299–318. https://doi.org/10.1007/978-90-481-3354-3_14.
Gworek, B., Bemowska-Kałabun, O., Kijeńska, M., Wrzosek-Jakubowska, J., 2016. Mercury in marine and oceanic waters—a review. Water Air Soil Pollut. 227, 371. https://doi.org/10.1007/s11270-016-3060-3.
Gworek, B., Dmuchowski, W., Baczewska-Dąbrowska, A.H., 2020. Mercury in the terrestrial environment: a review. Environ. Sci. Eur. 32, 128. https://doi.org/10.1186/s12302-020-00401-x.
Heimbürger, L.-E., Cossa, D., Marty, J.-C., Migon, C., Averty, B., Dufour, A., Ras, J., 2010. Methyl mercury distributions in relation to the presence of nano- and picophytoplankton in an oceanic water column (Ligurian Sea, North-western Mediterranean). Geochim. Cosmochim. Acta 74, 5549–5559. https://doi.org/10.1016/j.gca.2010.06.036.
Hobson, K.A., 1990. Stable isotope analysis of marbled murrelets: evidence for freshwater feeding and determination of trophic level. Condor 92, 897. https://doi.org/10.2307/1368725.
Hobson, K.A., Piatt, J.F., Pitocchelli, J., 1994. Using stable isotopes to determine seabird trophic relationships. J. Anim. Ecol. 63, 786. https://doi.org/10.2307/5256.
Holmes, P., James, K.A.F., Levy, L.S., 2009. Is low-level environmental mercury exposure of concern to human health? Sci. Total Environ. 408, 171–182. https://doi.org/10.1016/j.scitotenv.2009.09.043.
Ikemoto, T., Kunito, T., Tanaka, H., Baba, N., Miyazaki, N., Tanabe, S., 2004. Detoxification mechanism of heavy metals in marine mammals and seabirds: interaction of selenium with mercury, silver, copper, zinc, and cadmium in liver. Arch. Environ. Contam. Toxicol. 47 https://doi.org/10.1007/s00244-004-3188-9.
Jouanneau, W., Sebastiano, M., Rozen-Rechels, D., Harris, S.M., Blévin, P., Angelier, F., Brischoux, F., Gernigon, J., Lemesle, J.-C., Robin, F., Cherel, Y., Bustamante, P., Chastel, O., 2022. Blood mercury concentrations in four sympatric gull species from South Western France: insights from stable isotopes and biologging. Environ. Pollut. 308, 119619 https://doi.org/10.1016/j.envpol.2022.119619.
Kalisińska, E. (Ed.), 2019. Mammals and Birds as Bioindicators of Trace Element Contaminations in Terrestrial Environments: An Ecotoxicological Assessment of the Northern Hemisphere. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-00121-6.
Kim, E.Y., Saeki, K., Tanabe, S., Tanaka, H., Tatsukawa, R., 1996. Specific accumulation of mercury and selenium in seabirds. Environ. Pollut. 94, 261–265. https://doi.org/10.1016/S0269-7491(96)00110-8.
Kojadinovic, J., Bustamante, P., Churlaud, C., Cosson, R.P., Le Corre, M., 2007a. Mercury in seabird feathers: insight on dietary habits and evidence for exposure levels in the western Indian Ocean. Sci. Total Environ. 384, 194–204. https://doi.org/10.1016/j.scitotenv.2007.05.018.
Kojadinovic, J., Corre, M.L., Cosson, R.P., Bustamante, P., 2007b. Trace elements in three marine birds breeding on Reunion Island (Western Indian Ocean): part 1—factors influencing their bioaccumulation. Arch. Environ. Contam. Toxicol. 52, 418–430. https://doi.org/10.1007/s00244-005-0225-2.
Kojadinovic, J., Le Corre, M., Cosson, R.P., Salamolard, M., Bustamante, P., 2007c. Preliminary results on trace element levels in three species of seabirds from the western Indian Ocean. Ostrich 78, 435–441. https://doi.org/10.2989/OSTRICH.2007.78.2.50.130.
Kotnik, J., Horvat, M., Tessier, E., Ogrinc, N., Monperrus, M., Amouroux, D., Fajon, V., Gibičar, D., Žižek, S., Sprovieri, F., Pirrone, N., 2007. Mercury speciation in surface and deep waters of the Mediterranean Sea. Mar. Chem. 107, 13–30. https://doi.org/10.1016/j.marchem.2007.02.012.
Lavoie, R.A., Hebert, C.E., Rail, J.-F., Braune, B.M., Yumvihoze, E., Hill, L.G., Lean, D.R. S., 2010. Trophic structure and mercury distribution in a Gulf of St. Lawrence (Canada) food web using stable isotope analysis. Sci. Total Environ. 408, 5529–5539. https://doi.org/10.1016/j.scitotenv.2010.07.053.
Lavoie, R.A., Baird, C.J., King, L.E., Kyser, T.K., Friesen, V.L., Campbell, L.M., 2014. Contamination of mercury during the wintering period influences concentrations at breeding sites in two migratory piscivorous birds. Environ. Sci. Technol. 48, 13694–13702. https://doi.org/10.1021/es502746z.
Lavoie, R.A., Kyser, T.K., Friesen, V.L., Campbell, L.M., 2015. Tracking overwintering areas of fish-eating birds to identify mercury exposure. Environ. Sci. Technol. 49, 863–872. https://doi.org/10.1021/es502813t.
Lemesle, P., Jouanneau, W., Cherel, Y., Legroux, N., Ward, A., Bustamante, P., Chastel, O., 2024. Mercury exposure and trophic ecology of urban nesting black-legged kittiwakes from France. Chemosphere 363, 142813. https://doi.org/10.1016/j.chemosphere.2024.142813.
Lenth, R.V., Bolker, B., Buerkner, P., Giné-Vázquez, I., Herve, M., Jung, M., Love, J., Miguez, F., Riebl, H., Singmann, H., 2023. emmeans: Estimated Marginal Means, aka Least-squares Means.
Lequette, B., Weimerskirch, H., 1990. Influence of parental experience on the growth of wandering albatross chicks. Condor 92, 726. https://doi.org/10.2307/1368691.
Lippold, A., Aars, J., Andersen, M., Aubail, A., Derocher, A.E., Dietz, R., Eulaers, I., Sonne, C., Welker, J.M., Wiig, Ø., Routti, H., 2020. Two decades of mercury concentrations in Barents Sea polar bears (Ursus maritimus) in relation to dietary carbon, sulfur, and nitrogen. Environ. Sci. Technol. 54, 7388–7397. https://doi.org/10.1021/acs.est.0c01848.
Liu, G. (Ed.), 2012. Environmental Chemistry and Toxicology of Mercury. Wiley, Hoboken, NJ.
Lourenço, P.M., Granadeiro, J.P., Guilherme, J.L., Catry, T., 2015. Turnover rates of stable isotopes in avian blood and toenails: implications for dietary and migration studies. J. Exp. Mar. Biol. Ecol. 472, 89–96. https://doi.org/10.1016/j.jembe.2015.07.006.
Lucia, M., Bocher, P., Cosson, R.P., Churlaud, C., Bustamante, P., 2012. Evidence of species-specific detoxification processes for trace elements in shorebirds. Ecotoxicology 21, 2349–2362. https://doi.org/10.1007/s10646-012-0991-3.
Mason, R.P., Choi, A.L., Fitzgerald, W.F., Hammerschmidt, C.R., Lamborg, C.H., Soerensen, A.L., Sunderland, E.M., 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.
Mauffret, A., Chouvelon, T., Wessel, N., Cresson, P., Bănaru, D., Baudrier, J., Bustamante, P., Chekri, R., Jitaru, P., Le Loc'h, F., Mialet, B., Vaccher, V., Harmelin-Vivien, M., 2023. Trace elements, dioxins and PCBs in different fish species and marine regions: importance of the taxon and regional features. Environ. Res. 216, 114624 https://doi.org/10.1016/j.envres.2022.114624.
Médieu, A., Point, D., Itai, T., Angot, H., Buchanan, P.J., Allain, V., Fuller, L., Griffiths, S., Gillikin, D.P., Sonke, J.E., Heimbürger-Boavida, L.-E., Desgranges, M.-M., Menkes, C. E., Madigan, D.J., Brosset, P., Gauthier, O., Tagliabue, A., Bopp, L., Verheyden, A., Lorrain, A., 2022. Evidence that Pacific tuna mercury levels are driven by marine methylmercury production and anthropogenic inputs. Proc. Natl. Acad. Sci. 119, e2113032119 https://doi.org/10.1073/pnas.2113032119.
Médieu, A., Point, D., Sonke, J.E., Angot, H., Allain, V., Bodin, N., Adams, D.H., Bignert, A., Streets, D.G., Buchanan, P.B., Heimbürger-Boavida, L.-E., Pethybridge, H., Gillikin, D.P., Ménard, F., Choy, C.A., Itai, T., Bustamante, P., Dhurmeea, Z., Ferriss, B.E., Bourlès, B., Habasque, J., Verheyden, A., Munaron, J.-M., Laffont, L., Gauthier, O., Lorrain, A., 2024. Stable tuna mercury concentrations since 1971 illustrate marine inertia and the need for strong emission reductions under the Minamata Convention. Environ. Sci. Technol. Lett. 11, 250–258. https://doi.org/10.1021/acs.estlett.3c00949.
Mille, T., Wessel, N., Brun, M., Bustamante, P., Chouvelon, T., Méndez-Fernandez, P., Poiriez, G., Spitz, J., Mauffret, A., 2023. Development of an integrated indicator to assess chemical contamination in different marine species: The case of mercury on the French Atlantic continental shelf. Sci. Total Environ. 902, 165753 https://doi.org/10.1016/j.scitotenv.2023.165753.
Monteiro, L.R., Furness, R.W., 2001a. Kinetics, dose–response, and excretion of methylmercury in free-living adult Cory's shearwaters. Environ. Sci. Technol. 35, 739–746. https://doi.org/10.1021/es000114a.
Monteiro, L.R., Furness, R.W., 2001b. Kinetics, dose-response, excretion, and toxicity of methylmercury in free-living Cory's shearwater chicks. Environ. Toxicol. Chem. 20, 1816–1823. https://doi.org/10.1002/etc.5620200827.
Morris, A.D., Wilson, S.J., Fryer, R.J., Thomas, P.J., Hudelson, K., Andreasen, B., Blévin, P., Bustamante, P., Chastel, O., Christensen, G., Dietz, R., Evans, M., Evenset, A., Ferguson, S.H., Fort, J., Gamberg, M., Grémillet, D., Houde, M., Letcher, R.J., Loseto, L., Muir, D., Pinzone, M., Poste, A., Routti, H., Sonne, C., Stern, G., Rigét, F.F., 2022. Temporal trends of mercury in Arctic biota: 10 more years of progress in Arctic monitoring. Sci. Total Environ. 839, 155803 https://doi.org/10.1016/j.scitotenv.2022.155803.
Navarro, J., Grémillet, D., Ramirez, F., Afán, I., Bouten, W., Forero, M., 2017. Shifting individual habitat specialization of a successful predator living in anthropogenic landscapes. Mar. Ecol. Prog. Ser. 578, 243–251. https://doi.org/10.3354/meps12124.
Nelson, J.B., 1964. Factors influencing clutch-size and chick growth in the North Atlantic gannet *Sula bassana*. Ibis 106, 63–77. https://doi.org/10.1111/j.1474-919X.1964.tb03681.x.
Novotna Kruzikova, K., Siroka, Z., Kral, T., Hliwa, P., Gomulka, P., Spodniewska, A., Svobodova, Z., 2023. Mercury distribution in the great cormorant (Phalacrocorax carbo) from the Krogulna ponds and Nysa Kłodzka River (Poland). Vet. Med. 68, 164–174. https://doi.org/10.17221/16/2023-VETMED.
Obrist, D., Kirk, J.L., Zhang, L., Sunderland, E.M., Jiskra, M., Selin, N.E., 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.
Ochoa-acuña, H., Sepúlveda, M.S., Gross, T.S., 2002. Mercury in feathers from Chilean birds: Influence of location, feeding strategy, and taxonomic affiliation. Mar. Pollut. Bull. 44, 340–345. https://doi.org/10.1016/S0025-326X(01)00280-6.
Ogden, L.J.E., Hobson, K.A., Lank, D.B., 2004. Blood Isotopic (δ13C and δ15N) Turnover and Diet-Tissue Fractionation Factors in Captive Dunlin (Calidris Alpina Pacifica). The Auk 121, 170–177. https://doi.org/10.1093/auk/121.1.170.

Oppel, S., Powell, A.N., 2010. Carbon isotope turnover in blood as a measure of arrival time in migratory birds using isotopically distinct environments. J. Ornithol. 151, 123–131. https://doi.org/10.1007/s10336-009-0434-y.

Pereira, M.G., Lawlor, A., Bertolero, A., Díez, S., Shore, R.F., Lacorte, S., 2019. Temporal and spatial distribution of mercury in gulls eggs from the Iberian Peninsula. Arch. Environ. Contam. Toxicol. 76, 394–404. https://doi.org/10.1007/s00244-018-0584-0.

Peterson, S.H., Ackerman, J.T., Eagles-Smith, C.A., 2017. Mercury contamination and stable isotopes reveal variability in foraging ecology of generalist California gulls. Ecol. Indic. 74, 205–215. https://doi.org/10.1016/j.ecolind.2016.11.025.

Peterson, S.H., Ackerman, J.T., Toney, M., Herzog, M.P., 2019. Mercury concentrations vary within and among individual bird feathers: a critical evaluation and guidelines for feather use in mercury monitoring programs. Environ. Toxicol. Chem. 38, 1164–1187. https://doi.org/10.1002/etc.4430.

Pickhardt, P.C., Folt, C.L., Chen, C.Y., Klaue, B., Blum, J.D., 2002. Algal blooms reduce the uptake of toxic methylmercury in freshwater food webs. Proc. Natl. Acad. Sci. 99, 4419–4423. https://doi.org/10.1073/pnas.072531099.

Post, D.M., 2002. Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology 83, 703–718. https://doi.org/10.1890/0012-9658(2002)083[0703:USITET]2.0.CO;2.

Pinheiro, J., Bates, D., R Core Team, 2023. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1–162. Available at. https://cran.r-project.org/package=nlme. (Accessed 28 March 2023).

R Core Team, 2020. R Foundation for Statistical Computing Vienna Austria. R version 4.2.2. URL. https://www.R-project.org/.

Ramos, R., Ramírez, F., Sanpera, C., Jover, L., Ruiz, X., 2009. Feeding ecology of yellow-legged gulls Larus michahellis in the western Mediterranean: a comparative assessment using conventional and isotopic methods. Mar. Ecol. Prog. Ser. 377, 289–297. https://doi.org/10.3354/meps07792.

Renedo, M., Amouroux, D., Duval, B., Carravieri, A., Tessier, E., Barre, J., Bérail, S., Pedrero, Z., Cherel, Y., Bustamante, P., 2018. Seabird tissues as efficient biomonitoring tools for Hg isotopic investigations: implications of using blood and feathers from chicks and adults. Environ. Sci. Technol. 52, 4227–4234. https://doi.org/10.1021/acs.est.8b00422.

Renedo, M., Pedrero, Z., Amouroux, D., Cherel, Y., Bustamante, P., 2021. Mercury isotopes of key tissues document mercury metabolic processes in seabirds. Chemosphere 263, 127777. https://doi.org/10.1016/j.chemosphere.2020.127777.

Ricca, M.A., Keith Miles, A., Anthony, R.G., 2008. Sources of organochlorine contaminants and mercury in seabirds from the Aleutian archipelago of Alaska: inferences from spatial and trophic variation. Sci. Total Environ. 406, 308–323. https://doi.org/10.1016/j.scitotenv.2008.06.030.

Robinson, S.A., Lajeunesse, M.J., Forbes, M.R., 2012. Sex differences in mercury contamination of birds: testing multiple hypotheses with meta-analysis. Environ. Sci. Technol. 46, 7094–7101. https://doi.org/10.1021/es204032m.

Sakamoto, M., Murata, K., Kakita, A., Sasaki, M., 2011. A review of mercury toxicity with special reference to methylmercury, in: Environmental Chemistry and Toxicology of Mercury. John Wiley & Sons, Ltd, pp. 501–516. doi:https://doi.org/10.1002/9781118146644.ch15.

Sánchez-Fortún, M., Ouled-Cheikh, J., Jover, C., García-Tarrasón, M., Carrasco, J.L., Sanpera, C., 2020. Following up mercury pollution in the Ebro Delta (NE Spain): Audouin's gull fledglings as model organisms to elucidate anthropogenic impacts on the environment. Environ. Pollut. 266, 115232 https://doi.org/10.1016/j.envpol.2020.115232.

Sanpera, C., Moreno, R., Ruiz, X., Jover, L., 2007. Audouin's gull chicks as bioindicators of mercury pollution at different breeding locations in the western Mediterranean. Mar. Pollut. Bull. 54, 691–696. https://doi.org/10.1016/j.marpolbul.2007.01.016.

Santos, C.S.A., Sotillo, A., Gupta, T., Delgado, S., Müller, W., Stienen, E.W.M., Neve, L., Lens, L., Soares, A.M.V.M., Monteiro, M.S., Loureiro, S., 2020. Mercury Uptake Affects the Development of *Larus fuscus* Chicks. Environ. Toxicol. Chem. 39, 2008–2017. https://doi.org/10.1002/etc.4823.

Schartup, A.T., Soerensen, A.L., Angot, H., Bowman, K., Selin, N.E., 2022. What are the likely changes in mercury concentration in the Arctic atmosphere and ocean under future emissions scenarios? Sci. Total Environ. 836, 155477 https://doi.org/10.1016/j.scitotenv.2022.155477.

Scheuhammer, A.M., Meyer, M.W., Sandheinrich, M.B., Murray, M.W., 2007. Effects of environmental methylmercury on the health of wild birds, mammals, and fish. AMBIO J. Hum. Environ. 36, 12–19. https://doi.org/10.1579/0044-7447(2007)36[12:EOEMOT]2.0.CO;2.

Schimmelmann, A., Qi, H., Coplen, T.B., Brand, W.A., Fong, J., Meier-Augenstein, W., Kemp, H.F., Toman, B., Ackermann, A., Assonov, S., Aerts-Bijma, A.T., Brejcha, R., Chikaraishi, Y., Darwish, T., Elsner, M., Gehre, M., Geilmann, H., Gröning, M., Hélie, J.-F., Herrero-Martín, S., Meijer, H.A.J., Sauer, P.E., Sessions, A.L., Werner, R. A., 2016. Organic reference materials for hydrogen, carbon, and nitrogen stable isotope-ratio measurements: caffeines, *n*-alkanes, fatty acid methyl esters, glycines, L-valines, polyethylenes, and oils. Anal. Chem. 88, 4294–4302. https://doi.org/10.1021/acs.analchem.5b04392.

Sebastiano, M., Bustamante, P., Costantini, D., Eulaers, I., Malarvannan, G., Mendez-Fernandez, P., Churlaud, C., Blévin, P., Hauselmann, A., Dell'Omo, G., Covaci, A., Eens, M., Chastel, O., 2016. High levels of mercury and low levels of persistent organic pollutants in a tropical seabird in French Guiana, the Magnificent frigatebird, Fregata magnificens. Environ. Pollut. 214, 384–393. https://doi.org/10.1016/j.envpol.2016.03.070.

Sebastiano, M., 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.

Sonke, J.E., Angot, H., Zhang, Y., Poulain, A., Björn, E., Schartup, A., 2023. Global change effects on biogeochemical mercury cycling. Ambio 52, 853–876. https://doi.org/10.1007/s13280-023-01855-y.

Souza, J.S., Kasper, D., Da Cunha, L.S.T., Soares, T.A., De Lira Pessoa, A.R., De Carvalho, G.O., Costa, E.S., Niedzielski, P., Torres, J.P.M., 2020. Biological factors affecting total mercury and methylmercury levels in Antarctic penguins. Chemosphere 261, 127713. https://doi.org/10.1016/j.chemosphere.2020.127713.

Streets, D.G., Horowitz, H.M., Lu, Z., Levin, L., Thackray, C.P., Sunderland, E.M., 2019. Five hundred years of anthropogenic mercury: spatial and temporal release profiles. Environ. Res. Lett. 14, 084004 https://doi.org/10.1088/1748-9326/ab281f.

Szumiło-Pilarska, E., Falkowska, L., Grajewska, A., Meissner, W., 2017. Mercury in feathers and blood of gulls from the southern Baltic coast. Poland. Water. Air. Soil Pollut. 228, 138. https://doi.org/10.1007/s11270-017-3308-6.

Tartu, S., Goutte, A., Bustamante, P., Angelier, F., Moe, B., Clément-Chastel, C., Bech, C., Gabrielsen, G.W., Bustnes, J.O., Chastel, O., 2013. To breed or not to breed: endocrine response to mercury contamination by an Arctic seabird. Biol. Lett. 9, 20130317 https://doi.org/10.1098/rsbl.2013.0317.

Tartu, S., Blévin, P., Bustamante, P., Angelier, F., Bech, C., Bustnes, J.O., Chierici, M., Fransson, A., Gabrielsen, G.W., Goutte, A., Moe, B., Sauser, C., Sire, J., Barbraud, C., Chastel, O., 2022. A U-turn for mercury concentrations over 20 years: how do environmental conditions affect exposure in Arctic seabirds? Environ. Sci. Technol. 56, 2443–2454. https://doi.org/10.1021/acs.est.1c07633.

Tavares, S., Xavier, J.C., Phillips, R.A., Pereira, M.E., Pardal, M.A., 2013. Influence of age, sex and breeding status on mercury accumulation patterns in the wandering albatross Diomedea exulans. Environ. Pollut. 181, 315–320. https://doi.org/10.1016/j.envpol.2013.06.032.

Thorne, L.H., Fuirst, M., Veit, R., Baumann, Z., 2021. Mercury concentrations provide an indicator of marine foraging in coastal birds. Ecol. Indic. 121, 106922 https://doi.org/10.1016/j.ecolind.2020.106922.

Ullrich, S.M., Tanton, T.W., Abdrashitova, S.A., 2001. Mercury in the aquatic environment: a review of factors affecting methylation. Crit. Rev. Environ. Sci. Technol. 31, 241–293. https://doi.org/10.1080/20016491089226.

Vander Zanden, M.J., Clayton, M.K., Moody, E.K., Solomon, C.T., Weidel, B.C., 2015. Stable isotope turnover and half-life in animal tissues: a literature synthesis. PLoS One 10, e0116182. https://doi.org/10.1371/journal.pone.0116182.

Wang, F., Outridge, P.M., Feng, X., Meng, B., Heimbürger-Boavida, L.-E., Mason, R.P., 2019. How closely do mercury trends in fish and other aquatic wildlife track those in the atmosphere? – implications for evaluating the effectiveness of the Minamata Convention. Sci. Total Environ. 674, 58–70. https://doi.org/10.1016/j.scitotenv.2019.04.101.

Wenzel, C., Adelung, D., Theede, H., 1996. Distribution and age-related changes of trace elements in kittiwake Rissa tridactyla nestlings from an isolated colony in the German Bight. North Sea. Sci. Total Environ. 193, 13–26. https://doi.org/10.1016/S0048-9697(96)05320-X.

Whitney, M.C., Cristol, D.A., 2017. Impacts of sublethal mercury exposure on birds: a detailed review. In: de Voogt, P. (Ed.), Reviews of Environmental Contamination and Toxicology, Reviews of Environmental Contamination and Toxicology, vol. 244. Springer International Publishing, Cham, pp. 113–163. https://doi.org/10.1007/398_2017_4.

Wiener, J.G., Krabbenhoft, D.P., Heinz, G.H., Scheuhammer, A.M., 2003. Ecotoxicology of mercury. In: Handbook of Ecotoxicology, Second edition, pp. 409–463. https://doi.org/10.1201/9781420032505.ch16.

Willie, S., Pihillagawa Gedara, I., Maxwell, P., Meija, J., Mester, Z., Yang, L., 2013. TORT-3: Lobster Hepatopancreas Reference Material for Trace Metals. https://doi.org/10.4224/crm.2013.tort-3.

Wolfe, M.F., Schwarzbach, S., Sulaiman, R.A., 1998. Effects of mercury on wildlife: a comprehensive review. Environ. Toxicol. Chem. 17, 146–160. https://doi.org/10.1002/etc.5620170203.

Yang, L., Willie, S., Grinberg, P., Pihillagawa Gedara, I., Clancy, V., Maxwell, P., McRae, G., Meija, J., Mester, Z., 2014. DOLT-5: Dogfish Liver Certified Reference Material for Trace Metals and Other Constituents. https://doi.org/10.4224/crm.2014.dolt-5.

Zorrozua, N., Monperrus, Mathilde, Aldalur, Asier, Castège, I., Diaz, B., Egunez, A., Galarza, A., Hidalgo, J., Milon, E., Sanpera, C., Arizaga, J., 2020. Relating trophic ecology and Hg species contamination in a resident opportunistic seabird of the Bay of Biscay. Environ. Res. 186, 109526 https://doi.org/10.1016/j.envres.2020.109526.

Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed effects models and extensions in ecology with R, Statistics for Biology and Health. Springer New York, New York, NY. doi:https://doi.org/10.1007/978-0-387-87458-6.