Environmental Research 282 (2025) 122102

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Mercury in white-tailed eagle nestlings from northern Norway (2013–2018): Toxicity risk and dietary drivers of exposure

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ARTICLE INFO

Keywords:
Ecotoxicology
Biomonitoring
Birds of prey
Heavy metal
Trace element

ABSTRACT

Mercury (Hg) pollution is a global environmental problem. Hg exposure is linked to adverse health effects such as neurotoxicity and reproductive impairments, making monitoring crucial for assessing toxicity risks to humans and wildlife. Top predators, such as the white-tailed eagle (*Haliaeetus albicilla*), are excellent biomonitors of environmental contamination due to their susceptibility of accumulating high levels of biomagnifying pollutants like Hg. In this study, body feathers of white-tailed eagle nestlings ($n = 217$) were sampled in northern Norway in 2013–2018. Feathers were analyzed for total Hg (THg) concentrations and stable isotopes of carbon (δ^{13}C) and nitrogen (δ^{15}N) to explore the influence of dietary ecology on Hg exposure. THg concentrations ranged between 0.96 and 4.85 μg g^{-1}, with approximately 11 % of the chicks exceeding 3.9 μg g^{-1}, the threshold value considered moderate risk for toxic effects. THg concentrations were similar across years, except for 2015, which had significantly higher levels; however, isotope values did not differ between years, suggesting this was not driven by dietary shifts. We found a significant and positive relationship between THg concentrations and δ^{15}N, supporting the biomagnifying property of Hg. Similarly, we detected a significant positive THg-δ^{13}C relationship, indicating higher Hg exposure with a more marine diet. We also found a significant and negative relationship between THg and wing length (age proxy), suggesting younger chicks have higher Hg concentrations than older chicks, likely due to mass dilution during chick growth. This study improves our understanding of Hg exposure and risk in a top predator along the Norwegian coast.

1. Introduction

Mercury (Hg) pollution from human activities such as fossil fuel combustion, mining, and smelting, is a global environmental problem (Driscoll et al., 2013). Elevated exposure to Hg in humans and wildlife is linked to adverse health effects such as neurotoxicity and reproductive impairments (Clarkson and Magos, 2006; Whitney and Cristol, 2018; Dietz et al., 2022) with developing and early life stages being particularly vulnerable (Driscoll et al., 2013). To protect human and wildlife health from Hg pollution, the Minamata Convention on Mercury was established in 2013 to limit anthropogenic use and emissions of Hg globally (Kessler, 2013). Despite international and local regulations that have curtailed the emissions and use of Hg over the past decades (Futsaeter and Wilson, 2013), factors such as redistribution, cycling, and complex biomagnification processes of Hg contribute to persistently elevated and in many cases even increasing Hg levels in biota (Chetelat et al., 2020; Evers et al., 2024). Therefore, continued monitoring in wildlife is crucial for assessing the ongoing risk of environmental Hg contamination.

In aquatic food webs, Hg is rapidly methylated by microbes into its organic and most toxic form, methylmercury (MeHg) (Ullrich et al., 2001). MeHg has a high potential to bioaccumulate in organisms and biomagnify through food chains, resulting in elevated concentrations in upper trophic species (Chetelat et al., 2020; Dietz et al., 2022; Evers

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https://doi.org/10.1016/j.envres.2025.122102
Received 27 March 2025; Received in revised form 5 June 2025; Accepted 6 June 2025
Available online 7 June 2025

et al., 2024). The white-tailed eagle *Haliaeetus albicilla* (hereafter WTE for simplicity) is Europe's largest eagle and a top predator in marine coastal and freshwater habitats (Cramp, 1980). Feeding mainly on fish, seabirds, and waterfowl (Ekblad et al., 2016; Dementavičius et al., 2020), the WTE is susceptible to elevated Hg exposure through its consumption of aquatic prey species (Douglas et al., 2012). Consequently, as a long-lived species, the WTE serves as a valuable biomonitor of environmental contamination. It is already a well-established species in ecotoxicological research, particularly in the Baltic Sea region, which has experienced high levels of contamination (Scharenberg and Struwe-Juhl, 2000; Helander et al., 2008; Sun et al. 2019, 2020; Hansen et al., 2023; Haque et al., 2023). However, multiyear studies on Hg exposure in WTEs from Norway are scarce, despite Norway having the largest WTE population in Europe (Hailer et al., 2006).

Since diet is the primary route of contaminant intake in wildlife, examining dietary habits and food sources is commonly done to understand their role in driving exposure to pollutants such as Hg (Chetelat et al., 2020). Conventional methods for examining diet in avian wildlife can be challenging and time-consuming, such as analysing pellets, observing prey brought to nests, or examining stomach contents (Jordan, 2005). As an alternative, the analysis of stable isotope ratios of carbon (δ^{13}C) and nitrogen (δ^{15}N) in biological tissues is commonly used to investigate dietary ecology (Inger and Bearhop, 2008). δ^{13}C values serve as a proxy for feeding habitat, e.g., distinguishing between terrestrial and marine carbon sources (Inger and Bearhop, 2008). δ^{15}N values are indicative of the trophic level, with higher δ^{15}N values corresponding to higher trophic levels (Inger and Bearhop, 2008). In general, feeding on prey higher up in the food chain (higher δ^{15}N) and on more marine prey (higher δ^{13}C) are associated with a higher mercury burden (Douglas et al., 2012).

In this study, we sampled body feathers from 217 WTE nestlings in northern Norway between 2013 and 2018 to analyze total Hg (THg) concentrations and bulk stable isotopes of carbon (δ^{13}C) and nitrogen (δ^{15}N). Feathers provide a non-destructive and minimally invasive method for assessing Hg contamination in developing nestlings (Lodenius and Solonen, 2013; Zabala et al., 2019). In addition, feathers are considered representative matrices for Hg exposure as 70–90 % of the total Hg body burden (primarily in the form of MeHg) is remobilized and sequestered into growing feathers (Espín et al., 2016). Furthermore, stable carbon and nitrogen isotopes in feathers provide a time-integrated measure of dietary intake, reflecting the incorporation of isotopes into the growing feather over a period of days to weeks (Bearhop et al., 2002). Compared to feathers from adult birds, nestling feathers have the advantage of reflecting Hg contamination and diet during a more well-defined period of time, i.e. the nestling period prior to sampling, and during the same time of year (Eulaers et al., 2011; Rymešová et al., 2020; Gómez-Ramírez et al., 2023). Finally, since the WTE is a territorial species, its nestlings provide insight into Hg contamination and diet within their local environment (Lodenius and Solonen, 2013). Our research objectives were to 1) investigate inter-annual variation in feather THg concentrations in WTE nestlings from northern Norway, 2) assess the influence of dietary ecology (proxied by δ^{13}C and δ^{15}N) on Hg

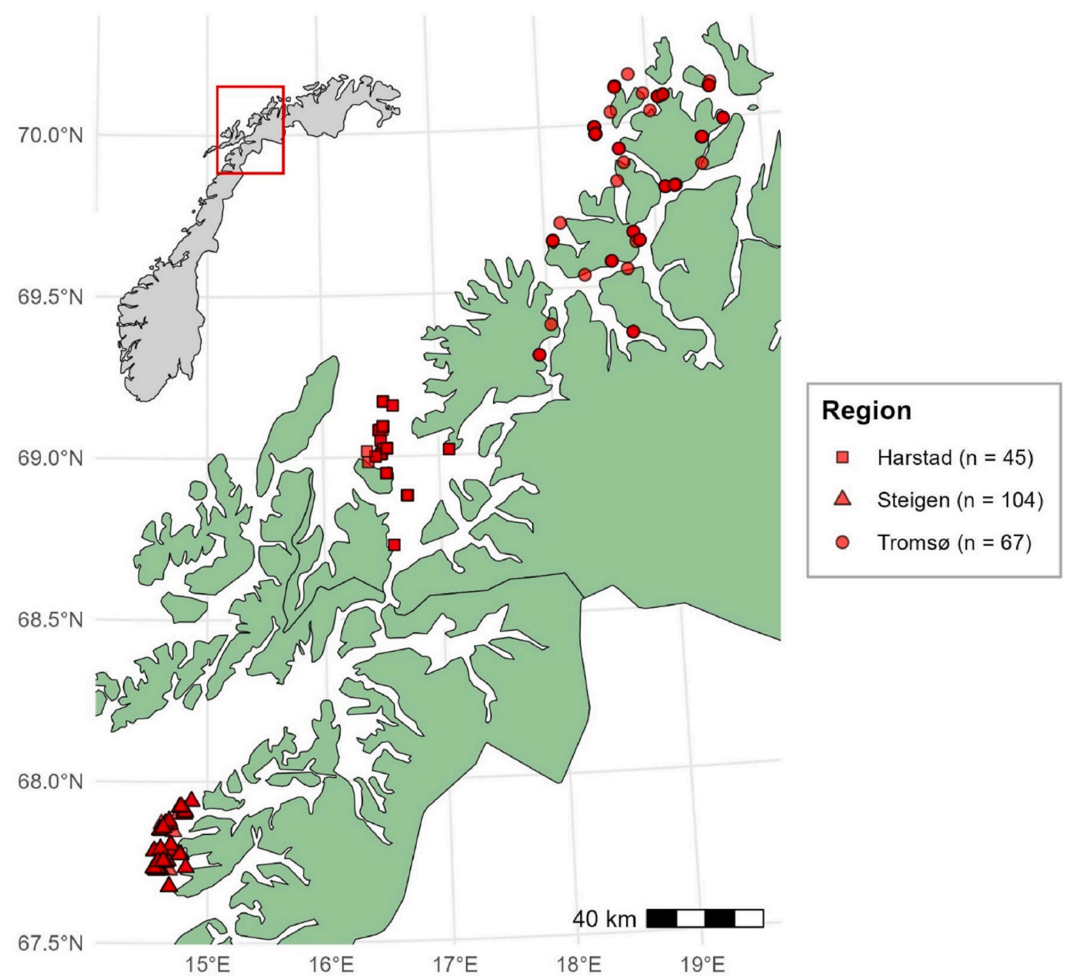

Fig. 1. Map of field sampling in different regions of northern Norway. Red shapes indicate sampling locations in areas surrounding Harstad (squares), Steigen (triangles) and Tromsø (circles), and the associated sample size per region in the legend box. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

exposure, and 3) evaluate potential Hg-associated toxicity risks.

2. Materials and methods

2.1. Data collection

Field sampling was conducted annually in the period 2013–2018 during late June or early July in different geographical regions of northern Norway: Tromsø, Harstad, and Steigen (Fig. 1). The WTE nests were accessed from sea or land, and all chicks in a brood (1–3 chicks) were captured at the nests approximately 5–9 weeks post-hatching. The chicks were morphometrically measured (wing length [cm] and body mass [g]) before sampling body feathers, five from the chest and five from the scapular area. For the present study, one scapular feather per chick was used for mercury and stable isotope analysis. The field sampling protocol was approved by the Norwegian Food Safety Authority (FOTS ID; 6432, 8709, 11944). In total 217 chicks were sampled across the study period.

2.2. THg analysis

Hg analysis was conducted at two laboratories: Aarhus University, Denmark (n = 154; 2013–2018, in all regions except Steigen in 2015 and 2016) and the Norwegian University of Science and Technology (NTNU), Norway (n = 34; 2015–2016, in Steigen only). All concentrations are reported as μg g^{-1} dry weight (dw).

At Aarhus University, total Hg (THg) analysis was performed at the Trace Element Lab, Department of Ecoscience. Body feather THg concentrations were determined using a Milestone DMA-80 Direct Mercury Analyzer (Sorisole, Italy) following U.S. EPA Method 7473. Sample preparation followed Bjedov et al. (2023). Briefly, the calamus was removed for genetic sexing, while the rachis and vane were washed in distilled water to remove external contamination. After drying overnight, feathers were cut into small pieces using cleaned surgical-steel forceps. A sample amount of 5.27 ± 0.42 mg (mean ± SD) of dry, homogenized feather material was analyzed. Analytical quality control was verified through procedural blanks, duplicates, aqueous standards (10 ng and 100 ng Hg, prepared from a 1000 ± 4 mg L^{-1} stock solution, Sigma-Aldrich, Switzerland), and Certified Reference Material (CRM; DORM-4, National Research Council, Ottawa, Canada). Procedural blanks and CRM samples were run every 10 samples. All samples were corrected for background Hg (0.07 ± 0.13 ng) and the recovery of aqueous standards (108.6 ± 1.3 %; n = 21). CRM recovery was 105.9 ± 2.3 % (n = 52) of the certified value (0.410 ± 0.055 μg g^{-1} dry weight), with a relative standard deviation of 8.28 ± 7.64 % (n = 13) for duplicate samples.

At the Department of Chemistry, NTNU, THg was analyzed as part of a multi-element analysis following the protocol described in Dolan et al. (2017) with modifications. One dorsal feather per individual was cut using a titanium knife to remove the calamus before being transferred to polypropylene tubes. A five-step washing procedure was applied with flushing twice with Milli-Q water in between the steps:1) chromatography grade acetone (5 min), 2) Milli-Q water (5 min), 3) acetone (5 min), 4) 0.64 M nitric acid (HNO_3, Ultrapure grade; 5 min), 5) Milli-Q water (5 min), followed by freezing at −20 °C. Samples were freeze-dried for at least 24 h, then transferred to perfluoroalkoxy (PFA) vessels, weighed, and digested with 1.5 ml of 50 % v/v concentrated HNO_3 in a high-pressure microwave system. After digestion, samples were diluted to 17 ml with Milli-Q water and analyzed using high-resolution inductively coupled plasma mass spectrometry (HR-ICP-MS, Thermo Scientific Element 2, Germany) with argon gas. Quality assurance included procedural blanks and standard reference materials (SRM), with SRM powder (tobacco leaves) from the Institute of Nuclear Chemistry and Technology, Warsaw, Poland (INCT-PVTL-6). The Reference material recovery for Hg was 87 %.

2.3. Stable isotope analysis

Stable isotope analysis was conducted at two laboratories: the University of Liège, Belgium (2013–2016 samples) and the University of Koblenz-Landau, Germany (2017–2018 samples). In brief, a subsample (1.52 ± 0.32 mg) was taken from a fine homogenate of an entire single washed body feather (weighing on average 62.04 mg as recorded for a subset), was crimped into a tin combustion cup and analyzed for stable isotope ratios of nitrogen and carbon. At the University of Koblenz-Landau, analysis was performed using a Flash 2000 HT elemental analyzer coupled via a ConFlo IV interface to a Delta V Advantage isotope ratio mass spectrometer (all Thermo Fisher Scientific, Bremen, Germany). At the University of Liège, a VarioMicro elemental analyzer was used, coupled to an Isoprime 100 isotope ratio mass spectrometer (Elementar, Germany).

The obtained stable carbon and nitrogen isotope ratios are conventionally expressed as δ-values (‰) relative to the international measurement standards Vienna Pee Dee Belemnite and atmospheric N_2, respectively. In University of Koblenz, internal reference material (i.e. casein) was measured in duplicate every ten samples, with a standard deviation of ≤0.06 ‰ for both δ^{13}C and δ^{15}N. In University of Liège, internal standard was glycine, interspread every 15 samples. Certified reference materials from the International Atomic Energy Agency (IAEA, Vienna, Austria), IAEA N-1 (ammonium sulphate; δ^{15}N = 0.4 ± 0.2 ‰), IAEA C-6 (sucrose; δ^{13}C = −10.8 ± 0.5 ‰) were inserted in each sample batch. A replicate of the same sample was included every 15 runs, with a standard deviation of 0.3 ‰ for both δ^{13}C and δ^{15}N. 196 feather samples from individual chicks were successfully analyzed for δ^{13}C and δ^{15}N values.

2.4. Statistical analysis

Data exploration and statistical analyses were performed using R version 4.4.1 (R Core Team, 2024). Data exploration and model diagnostics, including visual examination of residual plots, were performed following the protocol by Zuur et al. (2010). We considered one Hg value (0.08 μg g^{-1}) as an outlier, as it was 10 times lower than the second lowest measurement, and subsequently removed it from statistical analyses. Correlations among variables were examined to avoid multicollinearity (Supplementary information: Figure A.1), as placing correlated variables in the same model can lead to inflated uncertainty in parameter estimates (Zuur et al., 2010). δ^{13}C and δ^{15}N values were moderately correlated (Pearson's correlation coefficient: $r = 0.55$; $p < 0.01$; Figure A.1) and including both variables in the same model increased the uncertainty of the parameter estimates (results not shown), making it difficult to distinguish their individual effects. Therefore, we ran separate models where either δ^{13}C or δ^{15}N was included as a variable (Table 2).

We first tested for inter-annual variation in THg concentrations by running a linear model (function *lm*), with Year (a 6-level factor) as the independent variable (Supplementary information: Table A.1). We then performed a post-hoc Tukey test to compare means between years using the function *emmeans* in the *emmeans*-package (Lenth, 2025) (Table A.2.). Next, we chose linear mixed-effects models (function *lmer* in the *lme4*-package; Bates et al. (2015)) to investigate dietary drivers of Hg exposure in the WTE nestlings. P-values of the *lmer* object was retrieved using *lmerTest* (Kuznetsova et al., 2017). THg concentrations (response variable) were *ln*-transformed prior to analysis to meet the assumption of normality (Zuur et al., 2010). The fixed effects were δ^{15}N or δ^{13}C and wing length (age proxy; Helander (1981)), which was used to correct for developmental stage, as contaminant concentrations are known to decrease in tissues as chicks grow (Peterson et al., 2019). Although some nests contained more than one chick (2 or 3), potentially creating a problem of pseudo-replication, a large proportion of the nests (36 %) included only a single chick, which prevented us from estimating inter- and intra-nest variability in our analyses. Moreover, models that included nest ID as a random effect violated assumptions of normality and showed heteroscedastic residuals, making them unfit for reliable inference and weakening overall model performance (Zuur et al., 2010). Instead, since we had samples collected across 6 years (2013–2018) and in three geographical regions ('Tromsø', 'Harstad' and 'Steigen'; Fig. 1, Figure A.2), sampling year and region were considered as random effects in the model to account for potential temporal and spatial variability in Hg concentrations (Chen et al., 2008; Nickel et al., 2014). We determined the random effect structure by comparing candidate models using Akaike's Information Criterion (AIC) with the *aictab* function in the *AICcmodavg*-package (Mazzerolle, 2019). All candidate models had the same fixed effect structure but different random effect structure, and model selection was based on the lowest AICc value ($\Delta i \leq 2$; Anderson, 2008; Burnham et al., 2002). The random effect structure in the models were specified as follows.

- *Model 1*: Included 'year' as the only random effect to allow for different intercepts among sampling years.
- *Model 2*: Included 'region' as the only random effect to allow for different intercepts across regions.
- *Model 3*: Included 'region within year' as the random effect to allow for different intercepts across regions within each sampling year.

Model selection identified Model 3, which included 'region within year' as the random effect, as the most parsimonious model with the lowest ΔAICc value (Table A.3). Therefore, Model 3 best explained the observed variation in THg concentrations and was selected for inference.

Although having 196 datapoints for isotope values, and 187 datapoints for THg, the final dataset for the linear mixed-effect model included 176 observations with complete data for THg, δ^{13}C, and δ^{15}N after accounting for missing values (i.e., some observations had stable isotope data but lacked Hg measurements, and vice versa). All plots were produced using *ggplot2* (Wickham, 2016), and relationships between fixed effects and THg concentrations were visualized using the *ggpredict* function in the gg*effects*-package (Lüdecke, 2018) to display partial slopes and residuals for each fixed effect on fitted THg concentrations while holding the other predictor constant.

3. Results and discussion

3.1. Hg concentrations

Mean ± standard error (SE) THg concentration in WTE nestlings across the study period was 2.50 μg g^{-1} ± 0.07, with individual concentrations ranging from 0.96 to 4.85 μg g^{-1} (Table 1). The highest mean annual concentration was observed in 2015 (3.53 μg g^{-1} ± 0.17) and was significantly higher (Table A.1; $p < 0.01$) than the mean concentrations in other years, which were relatively similar, ranging from 2.15 to 2.56 μg g^{-1} (Table 1, Fig. 2). Inter-annual variability in Hg concentrations in wildlife can result from a combination of environmental and ecological factors, including fluctuations in climate conditions (e.g., temperature and solar radiation), atmospheric Hg deposition, and food web dynamics such as changes in prey availability or composition (Douglas et al., 2012; Fisher et al., 2013; Chetelat et al., 2020). However, the stable isotope values in this study suggest that diet was not the cause of elevated concentrations in 2015, as both δ^{13}C and δ^{15}N remained stable over time, with no notable deviation in 2015 (Figures A.3a, b). Therefore, other environmental factors not directly measured in this study such as climatic variables affecting Hg cycling and atmospheric deposition, may have contributed to the elevated Hg concentrations in that year.

The THg concentrations observed in WTE nestlings in this study are lower than those previously reported for adult WTEs in Norway, which had a mean feather Hg concentration of 4.69 μg g^{-1} between 2006 and 2015 (Sun et al., 2019). The higher concentrations in feathers of adults compared to nestlings likely reflect age-related influences on Hg

Table 1
Mean ± standard error (SE) and range (min-max) in feather concentrations of total mercury (THg, in dry weight) and bulk stable isotope values of nitrogen (δ^{15}N [‰]) and carbon (δ^{13}C [‰]) across the study period. The number of chicks, nests, and individuals varies because not all samples could be analyzed for both mercury and stable isotopes. The methods section specifies the number of samples and analyses for each variable.

Year	*n* chicks	*n* nests	THg Mean ± SE (min-max)	δ^{15}N Mean ± SE (min-max)	δ^{13}C Mean ± SE (min-max)
2013	28	19	2.15 ± 0.14 (1.00–3.74)	14.55 ± 0.10 (13.87–15.63)	−18.44 ± 0.17 (−20.17 to −16.47)
2014	33	22	2.39 ± 0.18 (1.16–3.74)	14.29 ± 0.11 (13.03–15.19)	−18.54 ± 0.13 (−19.92 to −16.84)
2015	30	21	3.53 ± 0.17 (2.26–4.77)	14.12 ± 0.16 (11.55–15.16)	−18.50 ± 0.09 (−19.39 to −17.73)
2016	41	26	2.30 ± 0.11 (1.42–3.97)	13.77 ± 0.10 (12.50–14.83)	−19.16 ± 0.10 (−20.58 to −18.03)
2017	45	31	2.56 ± 0.15 (1.21–4.85)	13.99 ± 0.06 (12.63–14.89)	−18.70 ± 0.06 (−19.61 to −17.77)
2018	39	26	2.26 ± 0.16 (0.96–4.67)	14.18 ± 0.11 (13.06–15.95)	−18.59 ± 0.07 (−19.44 to −17.59)
Total	216	145	2.50 ± 0.07 (0.96–4.85)	14.13 ± 0.04 (11.55–15.95)	−18.68 ± 0.04 (−20.58 to −16.47)
			187[a]	196[a]	196[a]

[a] Number of successfully analyzed individuals.

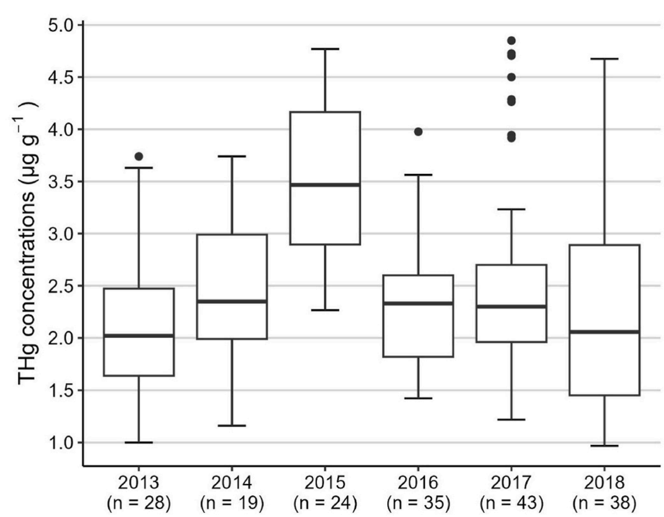

Fig. 2. Boxplots showing the median, 25th-75th quartiles (boxes) and minimum and maximum interquartile range (whiskers) in feather THg concentrations (μg g^{-1} dw.) per year. Black dots represent extreme values and are plotted individually. N total = 187.

accumulation (Thompson et al., 1991; Wood et al., 1996). As a long-lived species, WTEs are exposed to, and accumulate, Hg over decades, while moulting and egg-laying serve as primary elimination routes (Espín et al., 2016; Ackerman et al., 2020). Consequently, adult WTEs typically exhibit higher Hg burdens than nestlings, as demonstrated in the present study and by Sun et al. (2019).

Compared to WTE populations in other countries during similar time periods, Hg concentrations in Norwegian WTEs are relatively low (Sun et al., 2019; Ekblad et al., 2021; Bjedov et al., 2023). For example, a study on WTE nestlings in northern Finland reported mean feather Hg concentrations of 12.47 μg g^{-1} between 2007 and 2018 (Ekblad et al., 2021), while nestlings in Croatia had mean concentrations of 6.6 μg g^{-1}

over the period 2014–2018 (Bjedov et al., 2023), exceeding Hg concentrations observed in feathers of Norwegian nestlings (present study) and adults (Sun et al., 2019). In Finland, elevated Hg concentrations were primarily attributed to diet and proximity to contaminant sources, as WTEs foraged on pike from artificial lakes with elevated Hg concentrations (Ekblad et al., 2021). In Croatia, known Hg pollution sources related to agricultural and industrial activities were suggested as the main contributors to elevated levels (Bjedov et al., 2023). The lower Hg concentrations observed in Norwegian WTEs are consistent with findings from marine fish species in the Northeast Atlantic (Ho et al., 2021; Miljødirektoratet, 2022), many of which, such as Atlantic cod (*Gadus morhua*) and saithe (*Pollachius virens*), are common prey of WTEs (Eriksen, 2016). These species generally show relatively low Hg concentrations, with a clear north–south gradient indicating increasing Hg levels toward the south (Ho et al., 2021). In general, local Hg sources in Norway have been significantly reduced over the past 20–30 years due to strict regulations, leading to an 85 % reduction in atmospheric emissions since the 1990s (Miljødirektoratet, 2022). Therefore, Hg contamination in Norway at present is mainly considered a result of long-range atmospheric transport, with Norway receiving approximately three times more Hg from foreign sources than from domestic emissions (Berg et al., 2006).

3.2. Hg exposure in relation to diet and chick age

Analyzing stable isotope ratios of δ^{13}C and δ^{15}N has become a widely used method in ecotoxicology to identify pollution sources and understand their role as drivers of contaminant exposure in wildlife species (Eulaers et al., 2014; Badry et al., 2019; Gómez-Ramírez et al., 2023). In the present study, WTE chicks exhibited δ^{15}N values ranging from +11.55 to +15.95 ‰ (Table 1), suggesting they were fed prey from various trophic levels. Increasing trophic levels are typically associated with a 2–4 ‰ increase in δ^{15}N across each level (Inger and Bearhop, 2008), indicating that WTE chicks were consuming a mix of prey, for example piscivorous seabirds (e.g., cormorants, *Phalacrocorax* spp., and large gulls, *Laridae*), which are typically more enriched in ^{15}N compared to lower trophic prey such as piscivorous and omnivorous fish (e.g., Gadiformes, lumpsuckers) (Nadjafzadeh et al., 2016; Dementavičius et al., 2020). δ^{13}C values further suggest that the diet of WTE chicks was predominantly marine (Becker et al., 2007; Nilsen et al., 2008), with δ^{13}C values ranging from −20.58 to −16.47 ‰ (Table 1), consistent with their coastal habitat in northern Norway where marine prey likely dominate, although terrestrial prey cannot be excluded in the diet of a generalist and opportunistic predator like the WTE (Eriksen, 2016; Nadjafzadeh et al., 2016).

Our results showed a significant positive relationship between THg concentrations and δ^{15}N values, indicating that chicks that are fed higher trophic prey species tend to have higher THg concentrations ($p <$ 0.01; Table 2, Fig. 3A). Consistent with this, higher THg levels linked to more positive δ^{15}N values have been found in WTEs from other regions (Ekblad et al., 2021; Bjedov et al., 2023). A positive THg-δ^{15}N relationship is indicative of Hg biomagnification, which is a well-documented process in both marine and terrestrial food chains (Douglas et al., 2012; Dietz et al., 2022). Consequently, species feeding on higher trophic prey are more susceptible of accumulating harmful Hg levels. Furthermore, we detected a positive relationship between Hg and δ^{13}C values ($p < 0.01$; Table 2, Fig. 3B), which is expected, as predators with less negative δ^{13}C values (indicating a marine diet) tend to have higher Hg concentrations due to feeding in the marine environment (Chetelat et al., 2020).

We also observed a significant negative relationship between THg concentrations and wing length, showing that younger chicks had higher Hg concentrations than older ones ($p = 0.01$; Table 2, Fig. 3C). This pattern is consistent with findings for lipophilic contaminants and is likely a result of mass dilution (Bourgeon et al., 2013; Bustnes et al., 2013; Løseth et al., 2019; Hansen et al., 2020). As chicks grow, their internal Hg burdens are diluted with increasing body mass, leading to a decline in concentrations (Bustnes et al., 2013). This suggests that chicks are most vulnerable to toxic effects shortly after hatching, when maternally deposited Hg levels are highest (Ackerman et al., 2011). Over time, growth and feather excretion help reduce Hg body burdens (Ackerman et al., 2011). However, once feather growth is completed around fledging and post-fledging, contaminant levels often rise again, and Hg elimination through feathers will not occur until the next moult cycle (Ackerman et al., 2011; Rymešová et al., 2020).

Table 2
Parameter estimates including standard error (SE) from the linear mixed effect model investigating the relationship between feather THg concentrations (ln-transformed), stable isotopes (δ^{15}N and δ^{13}C [‰]) and wing length (proxy for chick age). The random effects were region within year (SD = standard deviation). The number of observations used to generate predictions in the model included 176 chicks with complete data for Hg, δ^{13}C, and δ^{15}N after accounting for missing values. P-value asterisks indicate significant effects (* < 0.05, ** < 0.01, *** < 0.001).

Response	Fixed Effects	Estimate	SE	t-value	p-value
THg	Intercept	−1.03	0.63	−1.62	0.10
	δ^{15}N (‰)	0.16	0.04	3.72	<0.01***
	Wing length (cm)	−0.01	0.00	−2.60	0.01*
	Random effects	**SD**			
	Year (Intercept)	0.20			
	Region:Year (Intercept)	0.13			
	Residual	0.30			
	Observations	176			
	Marginal/Conditional R^2	0.10/ 0.40			
THg	Intercept	3.74	0.83	4.48	<0.01***
	δ^{13}C (‰)	0.13	0.04	3.07	<0.01***
	Wing length (cm)	−0.01	0.00	−2.70	<0.01***
	Random effects	**SD**			
	Year (Intercept)	0.17			
	Region:Year (Intercept)	0.14			
	Residual	0.30			
	Observations	176			
	Marginal/Conditional R^2	0.08/ 0.40			

3.3. Toxicity risks

Although acute Hg toxicity in Norwegian WTEs is unlikely due to relatively low exposure levels, chronic exposure to moderate or even lower concentrations of Hg can lead to sublethal toxic effects (Whitney and Cristol, 2018). These include impairments to neurological (Bottini and MacDougall-Shackleton, 2023) and immune functions (e.g., Wayland et al. (2002); Fallacara et al. (2011); Lewis et al. (2013)), which may ultimately reduce individual survival and fitness (Whitney and Cristol, 2018). In the WTE, sublethal effects of Hg are suggested to be present in individuals having Hg concentrations in feathers in the range 5–40 μg g^{-1}, and concentrations >40 μg g^{-1} to be linked with impaired reproduction in adults (Scheuhammer, 1987; Gómez-Ramírez et al., 2023). However, a recent meta-analysis by Ackerman et al. (2024) calculated that feather Hg concentrations as low as 3.9 μg g^{-1} analyzed in chick down feathers fall within the moderate injury category, representing an effective concentration of 5 % (EC5). This threshold indicates that 5 % of individuals with Hg concentrations exceeding 3.9 μg g^{-1} are expected to experience toxic health effects (Ackerman et al., 2024).

In this study, the majority (88.8 %) of sampled WTE chicks had feather Hg concentrations below 3.9 μg g^{-1} (168 out of 187). However, 11.2 % of the chicks (21 out of 187) fell within the moderate injury category suggested by Ackerman et al. (2024), raising concerns about potential sublethal toxic effects, particularly in developing and vulnerable nestlings. It is important to note that the threshold established by Ackerman et al. (2024) was based on chick down feathers, which correlate more closely with Hg body burden and are less influenced by

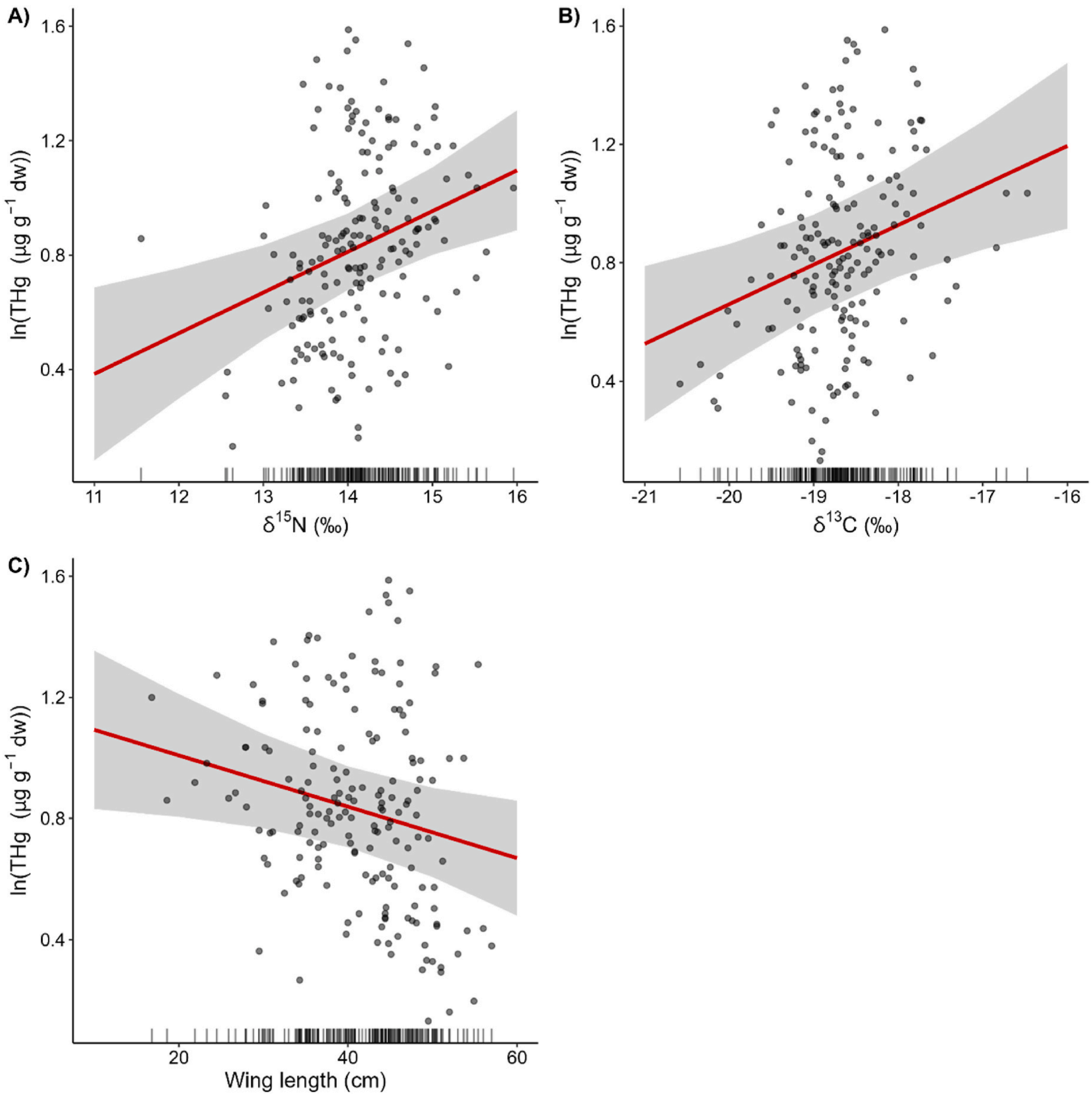

Fig. 3. Effect of A) $\delta^{15}N$, B) $\delta^{13}C$, and C) wing length on THg concentrations (ln-transformed) as predicted by the linear mixed effect models in Table 2. The graphs visualize the partial slope and residuals for each predictor, showing the effect on the fitted THg concentrations while holding the other predictors constant. The shaded area represents a pointwise 95 % confidence band for the fitted values, based on standard errors from the covariance matrix of the fitted regression coefficients. The rug plot at the bottom of each graph indicates the distribution of the individual raw data points (i.e., $\delta^{15}N$, $\delta^{13}C$, or wing length).

mass dilution and Hg sequestration than growing body feathers (Peterson et al., 2019). While this introduces some uncertainty, the threshold remains a valuable benchmark for assessing potential Hg risks in the WTE nestlings in our study and suggests that the toxicity threshold of >5.00 µg g^{-1} in adults (Scheuhammer, 1987) may be too conservative for chicks.

4. Conclusion

While most WTE nestlings in northern Norway between 2013 and 2018 had feather Hg concentrations below suggested thresholds for harmful effects, approximately 1 in 10 chicks exhibited concentrations above suggested moderate sublethal toxicity thresholds, raising concerns about potential adverse effects in some individuals. Potential vulnerability to Hg effects was highest in younger chicks, as well as in chicks feeding on higher-trophic prey (elevated $\delta^{15}N$ values) and a more marine diet (less negative $\delta^{13}C$ values).

Recent studies have shown that Hg concentrations in several marine predators are rising as a consequence of climate change (Foster et al., 2019) and shifts in prey availability (Schartup et al., 2019). These trends underscore the need for ongoing biomonitoring at both local and global scales to track environmental Hg pollution. In the context of a rapidly changing environment, continued monitoring of Hg contamination is therefore essential for predicting future ecotoxicological risks for WTE populations in Norway and elsewhere.

CRediT authorship contribution statement

Elisabeth Hansen: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Trond V. Johnsen:** Validation, Resources, Investigation. **Mari E. Løseth:** Investigation, Formal analysis. **Veerle L.B. Jaspers:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jens Søndergaard:** Writing – review & editing, Methodology. **Gilles Lepoint:** Writing – review & editing, Formal analysis. **Igor Eulaers:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Jan Ove Bustnes:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Funding sources

The data for this study were collected and analyzed as part of the following projects funded by the Research Council of Norway: The NewRaptor project (#230465), led by Prof. Dr. Veerle L. B. Jaspers, and the Ecostress project (#255681), led by Dr. Jan Ove Bustnes.

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.

Acknowledgments

We thank Jochen Zubrod for his involvement in the stable isotope analysis in University of Koblenz-Landau, Germany, and Syverin Lierhagen for conducting the ICP-MS analysis of feather mercury at the Department of Chemistry, NTNU, Norway. We also acknowledge the fieldworkers involved in data collection, with special thanks to Aasmund Gylseth for his contribution to field sampling in Steigen.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.122102.

Data availability

Data will be made available on request.

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.

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.

Ackerman, J.T., Peterson, S.H., Herzog, M.P., Yee, J.L., 2024. Methylmercury effects on birds: a review, meta-analysis, and development of toxicity reference values for injury assessment based on tissue residues and diet. Environ. Toxicol. Chem.

Anderson, D.R., 2008. Model Based Inference in the Life Sciences : a Primer on Evidence. Springer, New York ; London.

Badry, A., Palma, L., Beja, P., Ciesielski, T.M., Dias, A., Lierhagen, S., Jenssen, B.M., Sturaro, N., Eulaers, I., Jaspers, V.L.B., 2019. Using an apex predator for large-scale monitoring of trace element contamination: associations with environmental, anthropogenic and dietary proxies. Sci. Total Environ. 676, 746–755.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67, 1–48.

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.

Becker, B.H., Newman, S.H., Inglis, S., Beissinger, S.R., 2007. Diet–feather stable isotope (δ15N and δ13C) fractionation in common murres and other seabirds. Condor (Los Angel., Calif.) 109, 451–456.

Berg, T., Fjeld, E., Steinnes, E., 2006. Atmospheric mercury in Norway: contributions from different sources. Sci. Total Environ. 368, 3–9.

Bjedov, D., Mikuska, A., Begović, L., Bollinger, E., Bustnes, J.O., Deme, T., Mikuška, T., Morocz, A., Schulz, R., Søndergaard, J., Eulaers, I., 2023. Effects of white-tailed eagle (Haliaeetus albicilla) nestling diet on mercury exposure dynamics in Kopački rit Nature Park, Croatia. Environ. Pollut. 336, 122377.

Bottini, C.L.J., MacDougall-Shackleton, S.A., 2023. Methylmercury effects on avian brains. NeuroToxicology 96, 140–153.

Bourgeon, S., Leat, E.K.H., Furness, R.W., Borga, K., Hanssen, S.A., Bustnes, J.O., 2013. Dietary versus maternal sources of organochlorines in top predator seabird chicks: an experimental approach. Environ. Sci. Technol. 47, 5963–5970.

Burnham, K.P., Anderson, D.R., Burnham, K.P., 2002. Model Selection and Multimodel Inference : a Practical Information-theoretic Approach, second ed. Springer, New York.

Bustnes, J.O., Bardsen, B.J., Herzke, D., Johnsen, T.V., Eulaers, I., Ballesteros, M., Hanssen, S.A., Covaci, A., Jaspers, V.L., Eens, M., Sonne, C., Halley, D., Moum, T., Nost, T.H., Erikstad, K.E., Ims, R.A., 2013. Plasma concentrations of organohalogenated pollutants in predatory bird nestlings: associations to growth rate and dietary tracers. Environ. Toxicol. Chem. 32, 2520–2527.

Chen, C., Amirbahman, A., Fisher, N., Harding, G., Lamborg, C., Nacci, D., Taylor, D., 2008. Methylmercury in marine ecosystems: spatial patterns and processes of production, bioaccumulation, and biomagnification. EcoHealth 5, 399–408.

Chetelat, 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.

Clarkson, T.W., Magos, L., 2006. The toxicology of mercury and its chemical compounds. Crit. Rev. Toxicol. 36, 609–662.

Cramp, S., 1980. 2: hawks to bustards. Handbook of the Birds of Europe, the Middle East and North Africa: the Birds of the Western Palearctic. Oxford University Press.

Dementavičius, D., Rumbutis, S., Virbickas, T., Vaitkuvienė, D., Dagys, M., Treinys, R., 2020. Spatial and temporal variations in the White-tailed Eagle Haliaeetus albicilla breeding diet revealed by prey remains. Bird Study 67, 206–216.

Dietz, R., Letcher, R.J., Aars, J., Andersen, M., Boltunov, A., Born, E.W., Ciesielski, T.M., Das, K., Dastnai, S., Derocher, A.E., Desforges, J.-P., Eulaers, I., Ferguson, S., Hallanger, I.G., Heide-Jørgensen, M.P., Heimbürger-Boavida, L.-E., Hoekstra, P.F., Jenssen, B.M., Kohler, S.G., Larsen, M.M., Lindstrøm, U., Lippold, A., Morris, A., Nabe-Nielsen, J., Nielsen, N.H., Peacock, E., Pinzone, M., Rigét, F.F., Rosing-Asvid, A., Routti, H., Siebert, U., Stenson, G., Stern, G., Strand, J., Søndergaard, J., Treu, G., Víkingsson, G.A., Wang, F., Welker, J.M., Wiig, Ø., Wilson, S.J., Sonne, C., 2022. A risk assessment review of mercury exposure in Arctic marine and terrestrial mammals. Sci. Total Environ. 829, 154445.

Dolan, K.J., Ciesielski, T.M., Lierhagen, S., Eulaers, I., Nygård, T., Johnsen, T.V., Gómez-Ramírez, P., García-Fernández, A.J., Bustnes, J.O., Ortiz-Santaliestra, M.E., Jaspers, V.L.B., 2017. Trace element concentrations in feathers and blood of Northern goshawk (Accipiter gentilis) nestlings from Norway and Spain. Ecotoxicol. Environ. Saf. 144, 564–571.

Douglas, T.A., Loseto, L.L., Macdonald, R.W., Outridge, P., Dommergue, A., Poulain, A., Amyot, M., Barkay, T., Berg, T., Chételat, J., Constant, P., Evans, M., Ferrari, C., Gantner, N., Johnson, M.S., Kirk, J., Kroer, N., Larose, C., Lean, D., Nielsen, T.G., Poissant, L., Rognerud, S., Skov, H., Sørensen, S., Wang, F., Wilson, S., Zdanowicz, C. M., 2012. The fate of mercury in Arctic terrestrial and aquatic ecosystems, a review. Environ. Chem. 9, 321–355.

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.

Ekblad, C., Eulaers, I., Schulz, R., Stjernberg, T., Søndergaard, J., Zubrod, J., Laaksonen, T., 2021. Spatial and dietary sources of elevated mercury exposure in white-tailed eagle nestlings in an Arctic freshwater environment. Environ. Pollut. 290, 117952.

Ekblad, C.M., Sulkava, S., Stjernberg, T.G., Laaksonen, T.K., 2016. Landscape-scale gradients and temporal changes in the prey species of the White-tailed Eagle (Haliaeetus albicilla). In: Annales Zoologici Fennici. BioOne, pp. 228–240.

Eriksen, E., 2016. Diet and Activity Pattern of the white-tailed Eagle (Haliaeetus albicilla) Under the Midnight Sun. Norwegian University of Life Sciences, Ås. Master thesis.

Espín, S., García-Fernández, A.J., Herzke, D., Shore, R.F., van Hattum, B., Martínez-López, E., Coeurdassier, M., Eulaers, I., Fritsch, C., Gómez-Ramírez, P., Jaspers, V.L. B., Krone, O., Duke, G., Helander, B., Mateo, R., Movalli, P., Sonne, C., van den Brink, N.W., 2016. Tracking pan-continental trends in environmental contamination using sentinel raptors—what types of samples should we use? Ecotoxicology (Lond.) 25, 777–801.

Eulaers, I., Covaci, A., Herzke, D., Eens, M., Sonne, C., Moum, T., Schnug, L., Hanssen, S. A., Johnsen, T.V., Bustnes, J.O., Jaspers, V.L., 2011. A first evaluation of the usefulness of feathers of nestling predatory birds for non-destructive biomonitoring of persistent organic pollutants. Environ. Int. 37, 622–630.

Eulaers, I., Jaspers, V.L.B., Halley, D.J., Lepoint, G., Nygard, T., Pinxten, R., Covaci, A., Eens, M., 2014. Brominated and phosphorus flame retardants in white-tailed eagle *Haliaeetus albicilla* nestlings: bioaccumulation and associations with dietary proxies (delta C-13, delta N-15, and delta S-34). Sci. Total Environ. 478, 48–57.

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 (Lond.).

Fallacara, D.M., Halbrook, R.S., French, J.B., 2011. Toxic effects of dietary methylmercury on immune function and hematology in American kestrels (Falco sparverius). Environ. Toxicol. Chem. 30, 1320–1327.

Fisher, J.A., Jacob, D.J., Soerensen, A.L., Amos, H.M., Corbitt, E.S., Streets, D.G., Wang, Q., Yantosca, R.M., Sunderland, E.M., 2013. Factors driving mercury variability in the Arctic atmosphere and ocean over the past 30 years. Glob. Biogeochem. Cycles 27, 1226–1235.

Foster, K.L., Braune, B.M., Gaston, A.J., Mallory, M.L., 2019. Climate influence on mercury in Arctic seabirds. Sci. Total Environ. 693, 133569.

Futsaeter, G., Wilson, S., 2013. The UNEP global mercury assessment: sources, emissions and transport. In: E3S Web of Conferences. EDP Sciences, 36001.
Gómez-Ramírez, P., Bustnes, J.O., Eulaers, I., Johnsen, T.V., Lepoint, G., Pérez-García, J. M., García-Fernández, A.J., Espín, S., Jaspers, V.L.B., 2023. Mercury exposure in birds of prey from Norway: relation to stable carbon and nitrogen isotope signatures in body feathers. Bull. Environ. Contam. Toxicol. 110, 100.
Hailer, F., Helander, B., Folkestad, A.O., Ganusevich, S.A., Garstad, S., Hauff, P., Koren, C., Nygard, T., Volke, V., Vila, C., Ellegren, H., 2006. Bottlenecked but long-lived: high genetic diversity retained in white-tailed eagles upon recovery from population decline. Biol. Lett. 2, 316–319.
Hansen, E., Huber, N., Bustnes, J.O., Herzke, D., Bardsen, B.J., Eulaers, I., Johnsen, T.V., Bourgeon, S., 2020. A novel use of the leukocyte coping capacity assay to assess the immunomodulatory effects of organohalogenated contaminants in avian wildlife. Environ. Int. 142, 105861.
Hansen, E., Sun, J., Helander, B., Bustnes, J.O., Eulaers, I., Jaspers, V.L.B., Covaci, A., Eens, M., Bourgeon, S., 2023. A retrospective investigation of feather corticosterone in a highly contaminated white-tailed eagle (*Haliaeetus albicilla*) population. Environ. Res. 228, 115923.
Haque, F., Soerensen, A.L., Sköld, M., Awad, R., Spaan, K.M., Lauria, M.Z., Plassmann, M. M., Benskin, J.P., 2023. Per- and polyfluoroalkyl substances (PFAS) in white-tailed sea eagle eggs from Sweden: temporal trends (1969–2021), spatial variations, fluorine mass balance, and suspect screening. Environ. Sci.: Process. Impacts 25, 1549–1563.
Helander, B., 1981. Nestling measurements and weights from 2 white-tailed eagle populations in Sweden. Bird Study 28, 235–241.
Helander, B., Bignert, A., Asplund, L., 2008. Using raptors as environmental sentinels: monitoring the white-tailed sea eagle *Haliaeetus albicilla* in Sweden. Ambio 37, 425–431.
Ho, Q.T., Bank, M.S., Azad, A.M., Nilsen, B.M., Frantzen, S., Boitsov, S., Maage, A., Kögel, T., Sanden, M., Frøyland, L., Hannisdal, R., Hove, H., Lundebye, A.-K., Nøstbakken, O.J., Madsen, L., 2021. Co-occurrence of contaminants in marine fish from the North East Atlantic Ocean: implications for human risk assessment. Environ. Int. 157, 106858.
Inger, R., Bearhop, S., 2008. Applications of stable isotope analyses to avian ecology. Ibis (Lond., 1859) 150, 447–461.
Jordan, M.J.R., 2005. Dietary analysis for mammals and birds: a review of field techniques and animal-management applications. Int. Zoo Yearbk. 39, 108–116.
Kessler, R., 2013. The Minamata convention on mercury: a first step toward protecting future generations. Environ. Health Perspect. 121, A304–A309.
Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in Linear mixed effects models. J. Stat. Software 82, 1–26.
Lenth, R., 2025. Emmeans: Estimated Marginal Means, Aka Least-Squares Means.
Lewis, C.A., Cristol, D.A., Swaddle, J.P., Varian-Ramos, C.W., Zwollo, P., 2013. Decreased immune response in zebra finches exposed to sublethal doses of mercury. Arch. Environ. Contam. Toxicol. 64, 327–336.
Lodenius, M., Solonen, T., 2013. The use of feathers of birds of prey as indicators of metal pollution. Ecotoxicology (Lond.) 22, 1319–1334.
Lüdecke, D., 2018. Ggeffects: tidy data frames of marginal effects from regression models. J. Open Source Softw. 3, 772.
Løseth, M.E., Briels, N., Eulaers, I., Nygard, T., Malarvannan, G., Poma, G., Covaci, A., Herzke, D., Bustnes, J.O., Lepoint, G., Jenssen, B.M., Jaspers, V.L.B., 2019. Plasma concentrations of organohalogenated contaminants in white-tailed eagle nestlings - the role of age and diet. Environ. Pollut. 246, 527–534.
Mazzerolle, M.J., 2019. AICcmodavg: model selection and multimodel inference based on (Q)AIC(c). R package version 2.2-1.
Miljødirektoratet, 2022. National Mercury Assessment: an Evaluation of the Effectiveness of Norwegian Mercury Regulations and Policies. Norwegian Environmental Agency.
Nadjafzadeh, M., Voigt, C.C., Krone, O., 2016. Spatial, seasonal and individual variation in the diet of White-tailed Eagles Haliaeetus albicilla assessed using stable isotope ratios. Ibis (Lond., 1859) 158, 1–15.
Nickel, S., Hertel, A., Pesch, R., Schröder, W., Steinnes, E., Uggerud, H.T., 2014. Modelling and mapping spatio-temporal trends of heavy metal accumulation in moss and natural surface soil monitored 1990–2010 throughout Norway by multivariate generalized linear models and geostatistics. Atmos. Environ. 99, 85–93.
Nilsen, M., Pedersen, T., Nilssen, E.M., Fredriksen, S., 2008. Trophic studies in a high-latitude fjord ecosystem — a comparison of stable isotope analyses (δ13C and δ15N) and trophic-level estimates from a mass-balance model. Can. J. Fish. Aquat. Sci. 65, 2791–2806.
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.
R Core Team, 2024. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Rymešová, D., Pavlíček, D., Kirner, J., Mráz, J., Papoušek, I., Literák, I., 2020. Parentage analysis in the white-tailed eagle *Haliaeetus albicilla*: are moulted feathers from nest sites a reliable source of parental DNA? Acta Ornithol. 55, 41, 52, 12.
Scharenberg, W., Struwe-Juhl, B., 2000. Total mercury in feathers of white-tailed eagle (Haliaeetus albicilla L.) from Northern Germany over 50 years. Bull. Environ. Contam. Toxicol. 64, 686–692.
Schartup, A.T., Thackray, C.P., Qureshi, A., Dassuncao, C., Gillespie, K., Hanke, A., Sunderland, E.M., 2019. Climate change and overfishing increase neurotoxicant in marine predators. Nature 572, 648–650.
Scheuhammer, A.M., 1987. The chronic toxicity of aluminum, cadmium, Mercury, and lead in birds - a review. Environ. Pollut. 46, 263–295.
Sun, J.C., Bustnes, J.O., Helander, B., Bardsen, B.J., Boertmann, D., Dietz, R., Jaspers, V. L.B., Labansen, A.L., Lepoint, G., Schulz, R., Sondergaard, J., Sonne, C., Thorup, K., Tottrup, A.P., Zubrod, J.P., Eens, M., Eulaers, I., 2019. Temporal trends of mercury differ across three northern white-tailed eagle (*Haliaeetus albicilla*) subpopulations. Sci. Total Environ. 687, 77–86.
Sun, J.C., Covaci, A., Bustnes, J.O., Jaspers, V.L.B., Helander, B., Bardsen, B.J., Boertmann, D., Dietzf, R., Labansen, A.L., Lepoint, G., Schulz, R., Malarvannan, G., Sonne, C., Thorup, K., Tottrup, A.P., Zubrod, J.P., Eens, M., Eulaers, I., 2020. Temporal trends of legacy organochlorines in different white-tailed eagle (*Haliaeetus albicilla*) subpopulations: a retrospective investigation using archived feathers. Environ. Int. 138, 105618.
Thompson, D.R., Hamer, K.C., Furness, R.W., 1991. Mercury accumulation in great skuas Catharacta skua of known Age and sex, and its effects upon breeding and survival. J. Appl. Ecol. 28, 672–684.
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.
Wayland, M., Gilchrist, H., Marchant, T., Keating, J., Smits, J., 2002. Immune function, stress response, and body condition in arctic-breeding common eiders in relation to cadmium, mercury, and selenium concentrations. Environ. Res. 90, 47–60.
Whitney, M.C., Cristol, D.A., 2018. Impacts of sublethal mercury exposure on birds: a detailed review. In: de Voogt, P. (Ed.), Reviews of Environmental Contamination and Toxicology, ume 244. Springer International Publishing, pp. 113–163.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.
Wood, P.B., White, J.H., Steffer, A., Wood, J.M., Facemire, C.F., Percival, H.F., 1996. Mercury concentrations in tissues of Florida bald eagles. J. Wildl. Manag. 60, 178–185.
Zabala, J., Rodriguez-Jorquera, I.A., Orzechowski, S.C., Frederick, P., 2019. Mercury concentration in nestling feathers better predicts individual reproductive success than egg or nestling blood in a piscivorous bird. Environ. Sci. Technol. 53, 1150–1156.
Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14.