Marine Pollution Bulletin 234 (2027) 120572

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Seasonal variation in mercury contamination and feeding ecology in non-breeding common terns (*Sterna hirundo)*

M.S. Carrillo [a,b], D.I. Archuby [c], P. Bustamante [d,e], G. Castresana [f], M. Lunardelli [f], B. D'astek [a], D. Montalti [a,b], A.E. Ibañez [a,b,g,*]

[a] Sección Ornitología, Div. Zool. Vert., Museo de La Plata (FCNyM-UNLP), La Plata, Buenos Aires, Argentina
[b] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET-CCT La Plata), La Plata, Buenos Aires, Argentina
[c] Dirección de Biodiversidad, Ministerio de Ambiente de la Provincia de Buenos Aires (MAPBA), Buenos Aires, Argentina
[d] Littoral Environnement et Societes (LIENSs), La Rochelle Université, 2 rue Olympe de Gouges, 17000, La Rochelle, France
[e] Institut Universitaire de France (IUF), 1 rue Descartes, 75005, Paris, France
[f] Dirección de Áreas Naturales Protegidas, Ministerio de Ambiente de la Provincia de Buenos Aires (MAPBA), Buenos Aires, Argentina
[g] Departamento de Predadores Tope, Instituto Antártico Argentino (IAA), San Martín, Buenos Aires, Argentina

ARTICLE INFO

Keywords:
Pollutants
Stable isotopes
Seabirds
Non-breeding season
Physiology

ABSTRACT

Mercury (Hg) contamination in estuarine and coastal ecosystems represents a significant threat to wildlife due to its bioaccumulation and biomagnification across food webs. Particularly, Hg contamination of non-breeding migratory seabirds that inhabit these environments remains poorly documented, particularly at Neotropical latitudes. This study evaluated Hg contamination in relation to trophic ecology and physiology in Common terns (*Sterna hirundo*) at Punta Rasa, Bahía Samborombón, Buenos Aires, Argentina. Blood total Hg (THg), stable isotopes of carbon ($\delta^{13}C$) and sulfur ($\delta^{34}S$) as proxies of feeding habitat, and of nitrogen ($\delta^{15}N$) as a proxy of trophic position, biochemical markers of energy metabolism and body mass were assessed in individual sampled during three stages of the non-breeding season: *i*-early season (December), *ii*-mid-season (February), and *iii*-pre-migration period (April). Blood THg concentrations were quantified in all individuals (0.32–0.80 μg g^{-1} dry weight), increasing through the season. Stable isotope values varied seasonally and isotopic niches were wider in December than in February and April. Considering the month of the season, THg was positively associated with $\delta^{34}S$ and negatively associated with $\delta^{15}N$, whereas a positive trend with $\delta^{13}C$ was observed. These observations suggest that seasonal variation in feeding ecology and isotopic baselines may contribute to differences in Hg contamination. Body mass, triacylglycerol and cholesterol exhibited seasonal variations, nevertheless, under these blood THg concentrations no significant associations with the physiological markers were detected. Overall, our findings highlight the relevance of considering seasonal variation in feeding ecology and non-breeding habitats when assessing Hg contamination in migratory seabirds.

1. Introduction

Mercury (Hg) is a globally distributed environmental pollutant with well-documented adverse effects on human and wildlife health (Corsolini, 2009; Tan et al., 2009; Driscoll et al., 2013). Anthropogenic activities have increased Hg emissions and environmental concentrations, with atmospheric transport contributing to its widespread distribution across terrestrial and aquatic systems (Driscoll et al., 2013; Lamborg et al., 2014; Streets et al., 2019). Despite a decline observed in the Global North since the 1990s, including in China since the 2010s, anthropogenic emissions continue to rise, mainly due to emissions from the Global South, where those linked to artisanal and small-scale gold mining predominate (Qiu et al., 2025).

Estuaries are dynamic and highly productive transitional zones that link freshwater and marine environments (Kennish, 2002). Hg contamination in estuaries is of particular concern because these systems act as sinks for inorganic Hg (iHg) transported from large upstream watersheds (Gehrke et al., 2011; Singer et al., 2016) and provide physicochemical conditions that favour the microbial conversion of iHg into methylmercury (MeHg), its most bioavailable and toxic form

* Corresponding author at: Sección Ornitología, Div. Zool. Vert., Museo de La Plata (FCNyM-UNLP), Paseo del Bosque s/n, B1900FWA, La Plata, Buenos Aires, Argentina.
E-mail address: aeibanez@fcnym.unlp.edu.ar (A.E. Ibañez).

https://doi.org/10.1016/j.marpolbul.2026.120572
Received 10 September 2026; Received in revised form 25 October 2026; Accepted 8 November 2026
0025-326X/© 2026 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

(Lambertsson and Nilsson, 2006; Hall et al., 2008). Spatial and temporal variability in Hg concentrations within estuarine and coastal habitats is driven by freshwater currents, wind, rainfall, and inputs from rivers and wastewater (Ceyca et al., 2016; Cossa and Tabard, 2020; Liu et al., 2021), contributing to variation in Hg distribution and exposure among aquatic organisms.

MeHg bioaccumulates in organisms and biomagnifies through food webs (Lavoie et al., 2013; Tansel, 2026). Hence, organisms occupying high trophic positions, such as seabirds, are particularly useful as bioindicators of contaminant exposure due to their potential for contaminant bioaccumulation and biomagnification, as well as their wide spatial distribution (Kesic et al., 2023; Matos et al., 2023; Carrillo et al., 2023, 2025). Seabirds diet represents the primary route of Hg exposure (Bearhop et al., 2000; Bargagli, 2008; Mills et al., 2020, 2022; Ibañez et al., 2022). Particularly, piscivorous seabirds may exhibit spatially heterogeneous Hg exposure due to differences in their foraging habitats and prey, which can vary across coastal and offshore environments (Fort et al., 2014; Chételat et al., 2020; Bracey, 2021).

Hg contamination can cause both short- and long-term consequences for seabird health, fitness and population dynamics (Bustnes et al., 2007; Roos and Dencker, 2012; Chételat et al., 2020; Mills et al., 2020; Goutte et al., 2014a, 2014b), even at sublethal concentrations (Carravieri et al., 2022; Ibañez et al., 2024). As a neurological, immune, hepatic, and endocrine disruptor, Hg can also impair body condition and physiological performance (Tartu et al., 2013; Whitney and Cristol, 2017). However, most research on Hg contamination in seabirds has focused on the breeding season, when individuals are on their colonies, being much more easily accessible for sampling (Burger and Gochfeld, 2004; Ackerman et al., 2016), whereas the non-breeding period remains comparatively understudied, especially on blood-based assessments (Bracey, 2021; Bertram et al., 2022, 2024). Migratory seabirds exploit geographically distinct areas throughout their annual cycle, potentially encountering contrasting environmental conditions and food-web pathways of Hg exposure during the breeding and non-breeding periods (Fort et al., 2014; Fleishman et al., 2019; Carravieri et al., 2023). Consequently, assessments restricted to breeding populations may provide an incomplete representation of exposure across the annual cycle, particularly when the contribution of non-breeding areas to Hg accumulation and its potential carry-over effects remains poorly understood. Hg bioaccumulated during either the breeding or non-breeding period may generate carry-over effects influencing fitness in subsequent life-history stages (Quillfeldt et al., 2022; Carravieri et al., 2023). Therefore, assessing Hg contamination during different annual periods is critical to understand seasonal variation in exposure and its potential consequences in seabird health.

Ecotoxicological studies require an integrative understanding of trophic ecology, foraging ecology, and seasonal variation in Hg contamination. Stable isotope analysis provides a useful framework for investigating ecological drivers of Hg contamination in seabirds (Bearhop et al., 2000; Petalas et al., 2025). Carbon ($\delta^{13}C$) and sulfur ($\delta^{34}S$) stable isotopes provide complementary information on feeding habitat and resource origin, and their combined use can help distinguish among estuarine, coastal, and more marine food sources (Hobson et al., 1996; Cathalot et al., 2013; Phillips and Lewis, 2014; Ponton and Hare, 2015; Carr et al., 2017; Linhares et al., 2026). Particularly, sulfur stable isotopes ($\delta^{34}S$) distinguish freshwater, estuarine, and marine food sources based on differences in sulfate sources and sedimentary sulfur cycling (Carr et al., 2017). Nitrogen stable isotopes ($\delta^{15}N$) are commonly used as an indicator of trophic position (Peterson and Fry, 1987; Atwell et al., 1998; Lavoie et al., 2013), although spatial variation in isotopic baselines can complicate their interpretation along estuarine-coastal gradients (Fry, 2006; Popp et al., 2007). Therefore, seasonal variation in stable isotope composition can provide evidence of differences in feeding ecology but should not be interpreted as direct evidence of individual changes in foraging habitat. Because dietary Hg contamination is influenced by both trophic position and feeding habitat, combining stable isotope measurements with Hg concentrations can help identify ecological factors associated with Hg contamination (Bond, 2010; Albert et al., 2019; Mills et al., 2025). Moreover, both stable isotope values and blood THg integrate dietary information over time, such that measurements obtained early in the non-breeding season may retain signals from previous feeding areas in migratory birds (Hobson and Clark, 1992; Bearhop et al., 2002; Bond and Diamond, 2011).

Common terns (*Sterna hirundo*) are long-distance migratory seabirds that breed in the Northern Hemisphere and spend their non-breeding period in the Southern Hemisphere, where they primarily occupy estuarine and coastal habitats (Ludwig and Becker, 2006; Neves et al., 2015; Caldwell et al., 2025; Kiat et al., 2026). During this period, they feed mainly on small fish captured by plunge-diving. Studies at Punta Rasa described seasonal variation in diet and foraging strategies (Mauco and Favero, 2005; Lamacchia et al., 2019). The high reliance of this species on aquatic prey and the use of coastal and estuarine environments makes it a useful bioindicator for assessing contaminant exposure. At Punta Rasa, Argentine anchovy (*Engraulis anchoita*) is an important prey species that undergoes seasonal and ontogenetic changes in distribution across coastal and shelf waters Sanchez and de Ciechomski, 1995; Hansen and Madirolas, 1996). These changes may influence prey availability and feeding conditions for Common terns and potentially contribute to seasonal variation in Hg load. In Buenos Aires Province (Argentina), approximately 20,000–30,000 individuals congregate at Punta Rasa, Bahía Samborombón, a coastal site located at the confluence of the Rio de La Plata estuary and the Atlantic Ocean. This area is recognized as a wetland of international importance under the RAMSAR convention and as an important site for seabirds and shorebirds within the Western Hemisphere Shorebird Reserve Network (WHSRN), highlighting its ecological relevance for migratory birds. Its environmental heterogeneity and seasonal variation in the resources (Sapoznikow et al., 2002; Neves et al., 2015) provide an appropriate site to investigate seasonal variation in feeding ecology and contaminant exposure, thereby enabling a better understanding of the impact of such exposure on this important wetland.

This study aimed to evaluate seasonal variation in Hg contamination in non-breeding Common terns at Punta Rasa and its relationship with feeding ecology and physiological condition. Specifically, we (i) quantified blood THg concentrations across the non-breeding season, (ii) characterized seasonal variation in feeding ecology using $\delta^{13}C$, $\delta^{34}S$ and $\delta^{15}N$ and evaluated their relationships with THg, and (iii) examined whether THg concentrations were associated with body condition and physiological markers of energy metabolism. We hypothesized that: (i) blood THg concentrations vary among months of the non-breeding season; (ii) seasonal variation in blood THg concentrations is associated with variation in $\delta^{13}C$, $\delta^{34}S$, and $\delta^{15}N$ values, consistent with seasonal changes in feeding ecology; and (iii) higher THg concentrations are associated with changes in body mass and physiological markers related to energy metabolism.

2. Materials and methods

2.1. Study site

Fieldwork was conducted at Punta Rasa, Bahía Samborombón, Buenos Aires Province, Argentina (36°17′ S; 56°46′W), an intertidal area within the Río de La Plata estuary where marine and freshwater ecosystems converge. Such estuarine–coastal gradients are known to influence Hg cycling and methylation processes, potentially affecting contaminant bioavailability across habitats (Fitzgerald et al., 2007; Mason et al., 2012). This region hosts the largest coastal marine wetland in Argentina. Due to its high biodiversity, Punta Rasa constitutes a key habitat for migratory seabirds and has been designated as RAMSAR site, reflecting national and international conservation efforts aimed at protecting these wetlands and their resources. Additionally, is recognized as an Important Bird Area (IBA) by Aves Argentinas/BirdLife International

and has been declared a provincial protected area (Reserva Natural de Objetivo Definido Rincón de Ajó) by the Buenos Aires environmental authority (Law N° 12,016/97, Ministerio de Ambiente de la Provincia de Buenos Aires, MAPBA).

2.2. Sample collection

During the non-breeding season 2021–2022 (November to April), Common terns (*Sterna hirundo*) migrate from the Northern Hemisphere and establish at Punta Rasa. For this study, the sampling period was divided into three stages: early non-breeding season (December), mid-season (February), and pre-migration period (April). Birds were captured using cannon nets and handling time did not exceed 8 min to minimize stress responses. Morphometric measurements (weight, tarsus and culmen length) were recorded to estimate body condition. Blood samples ($n = 15$ per stage) were collected from the brachial vein (0.7 mL) using 25-G needles and stored at 4 °C for up to 6 h. Once in the laboratory, blood samples were centrifuged at 2000 rpm for 10 min, and serum and red blood cells (RBCs) were separated into sterile micro-centrifuge tubes and stored at −20 °C until analysis. Blood samples were selected as the target tissue because they reflect recent dietary exposure over a period of weeks and provides an indicator of short-term mercury uptake and trophic dynamics. All sampled birds were adults and represented unique individuals, with no recaptures included in our study. Because all birds were captured and banded for the first time, no previous information regarding the age or the sex was available. All procedures involving animal handling and sample collection were evaluated and approved by were evaluated and approved by the Environmental Impact Office of the Ministerio de Ambiente de la Provincia de Buenos Aires (MAPBA) (EX-2021-18,115,505-GDEBA-DGAOPDS and RESO–2022-18,115,505-GDEBA-SSTAYLMAMGP) and by the Institutional Committee for the Care and Use of Experimental Animals (CICUAE), Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata (FCNyM-UNLP; Protocol No. 003.03.2022).

2.3. Mercury analysis

In avian blood, Hg is primarily associated with the cellular fraction (RBCs) rather than serum (Bond and Robertson, 2015; Renedo et al., 2018). Previous studies have reported that MeHg accounts for more than 90% of Hg in blood (hereafter referred to as blood THg) in seabirds (Renedo et al., 2018; Albert et al., 2019). However, MeHg was not quantified directly in the present study, and this proportion could not be assessed. Prior to analysis, RBCs were freeze-dried and homogenized. THg concentrations were measured using an Advanced Mercury Analyzer spectrophotometer (AMA 254, Altec) at the LIENSs laboratory (France). For each sample, a minimum of two aliquots (range: 1.02–1.86 mg dry weight [dw]) were analysed. Quality control procedures included the analysis of certified reference materials, procedural blanks, and replicate samples to ensure analytical accuracy and precision. Analytical accuracy was verified every 10 samples using certified reference material (lobster hepatopancreas TORT-3, NRC, Canada; certified Hg concentration: 0.292 ± 0.022 μg g^{-1} dw), yielding a recovery of 98.1 ± 3.9%. Procedural blanks were included at the beginning of each analytical batch. The limit of quantification (LOQ) of the AMA was 0.1 ng Hg. Analytical precision was assessed by calculating the Coefficient of Variation (CV) for replicate measurements of each sample. The mean CV across the 45 samples analysed in duplicate was 1.61%. Results are further expressed as μg g^{-1} dw.

2.4. Carbon, nitrogen and sulfur stable isotope analysis

Stable isotope values of carbon, nitrogen and sulfur were determined in RBCs using a continuous-flow elemental analyzer (Delta V Plus with a Conflo IV Interface, Thermo Scientific, Bremen, Germany) coupled to an elemental analyzer (Flash 2000 or Flash IRMS EA Isolink CN, Thermo Scientific, Milan, Italy). Isotopic values were normalized using international reference standards to ensure analytical consistency and comparability across samples. Analyses were conducted at the LIENSs laboratory (France). Isotopic ratios are reported in delta (δ) notation in parts per thousand (‰) relative to international standards: Vienna Pee Dee Belemnite (VPDB) for $\delta^{13}C$, atmospheric nitrogen (AIR) for $\delta^{15}N$ and Vienna Canyon Diablo Troilite (VCDT) for $\delta^{34}S$ (Coplen, 2011). Calibration was performed using a two-point normalization. Analytical accuracy and precision were assessed using certified reference materials USGS61 ($\delta^{13}C = -35.05 \pm 0.04$ ‰; $\delta^{15}N = -2.87 \pm 0.04$ ‰), USGS63 ($\delta^{13}C = -1.17 \pm 0.04$ ‰; $\delta^{15}N = +37.83 \pm 0.06$ ‰) and USGS42 and IAEA-S2 ($\delta^{34}S = 7.84 \pm 0.25$ ‰ and 22.62 ± 0.09 ‰, respectively) provided by the U.S. Geological Survey (Reston, VA, USA). Measurement error was <0.10 ‰ for $\delta^{13}C$ and $\delta^{15}N$ and < 0.25 ‰ for $\delta^{34}S$.

2.5. Hematological determinations

Serum concentrations of energy metabolism markers including total proteins, uric acid, triacylglycerol, cholesterol, glucose and albumin were determined for each bird using colorimetric commercial kits (Wiener Lab). All determinations were conducted using an automatic analyzer (Ibañez et al., 2024).

Serum circulating levels of Immunoglobulin Y (IgY) were determined using a direct ELISA with peroxidase-conjugated anti-chicken IgY antibodies (Sigma, St. Louis, MO, USA, A-9046) (Martínez et al., 2003; Ibañez et al., 2024). For this, 96-well microtiter plates (Nunc PolySorp; Nunc, Roskilde, Denmark) were coated for 1 h at 37 °C with serum samples diluted (1:30,000) in 0.1 M carbonate-bicarbonate buffer (pH 9.6). The plates were then washed three times with PBS-0.05% Tween-20 and incubated with 1% non-fat milk (Nestlé Coffee-Mate) in PBS-Tween 20 for 1 h at 37 °C to block free binding sites. After additional washing, the wells were incubated with peroxidase-conjugated anti-chicken IgY. Finally, the wells were washed again, and ABTS [2,2-azino-di (3-ethylbenzthiazoline sulfonate)] was added as the substrate. Following a 30 min incubation at room temperature, colour development was stopped with 2% oxalic acid, and optical density (OD) was measured at 405 nm.

2.6. Statistical analysis

All statistical analyses were conducted in R (version 4.2.1; R Core Team, 2023). Seasonal variation in THg concentrations in red blood cells (RBCs) was evaluated using a linear model (LM), with sampling month (December, February, and April) as a categorical explanatory variable. Pairwise differences among months were assessed using *post-hoc* comparisons of estimated marginal means with Tukey adjustment for multiple comparisons, implemented in emmeans package in R.

Relationships between blood THg concentrations and stable isotope composition were evaluated using separate linear models for $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$. For each isotope, models were fitted with the corresponding isotope value and sampling month as additive predictors. Model residuals were assessed using graphical diagnostics, the Shapiro–Wilk test for normality, and the Fligner–Killeen test for homogeneity of variance.

Isotopic niches were quantified using standard ellipse areas (SEA) with small-sample correction (SEAc), calculated using the SIBER package (Jackson et al., 2011). Bayesian standard ellipse areas (SEAb) were also estimated to characterize posterior distributions of isotopic niche width for each month. Isotopic niche overlap among months was quantified using SEAc (Syväranta et al., 2013).

Associations between blood THg concentrations and physiological variables were evaluated separately for each physiological parameter, including blood THg concentration and sampling month as explanatory variables. Body mass, total proteins, triacylglycerols, uric acid, cholesterol, albumin, glucose, and IgY were analysed separately. Triacylglycerol concentrations were log-transformed prior to analysis. Linear models were used for variables meeting the assumptions of

homogeneous residual variance, whereas generalized least-squares (GLS) models with a heterogeneous variance structure by sampling month [varIdent(~1 | Month)] were used when heteroscedasticity was detected. Model assumptions were evaluated using the residuals of the final fitted models. Normality was assessed using diagnostic plots of the residuals from the final fitted models, the Shapiro–Wilk test and normal Q–Q plots, and homogeneity of variance was evaluated using the Fligner–Killeen test. For GLS models, normalized residuals were used to assess model adequacy. No observations were excluded based solely on statistical diagnostics (Supplementary Material). Statistical significance was set at $p < 0.05$.

3. Results

3.1. Blood THg concentrations

THg was quantified in all blood samples from Common terns (*Sterna hirundo*), with concentrations ranging from 0.32 to 0.80 μg g^{-1} dw (mean ± SD: 0.51 ± 0.10 μg g^{-1} dw). Blood THg concentrations differed significantly among samplings months ($F_{2,42} = 16.46$, $p < 0.001$). April showed significantly higher concentrations than both December and February (December vs. April: $t_{42} = 5.63$, $p < 0.001$; February vs. April: $t_{42} = 3.78$, $p = 0.001$), whereas no significant difference was detected between December and February ($t_{42} = 1.85$, $p = 0.166$; Fig. 1; Supplementary material, table S1;S3). Raw arithmetic mean THg concentrations increased by approximately 34% from December to April (Table 1).

3.2. Feeding ecology and hg contamination

From December to April, stable isotope values exhibited an enrichment pattern in RBCs, with increases of approximately 1.3 ‰ in $\delta^{13}C$, 2 ‰ in $\delta^{15}N$ and 1.1 ‰ in $\delta^{34}S$ (Table 1). Isotopic niche analyses showed monthly differences across all isotope combinations ($\delta^{13}C$-$\delta^{15}N$, $\delta^{13}C$-$\delta^{34}S$, and $\delta^{34}S$-$\delta^{15}N$). December exhibited the widest isotopic niche (SEAb = 1.264 for $\delta^{13}C$–$\delta^{15}N$; SEAb = 0.602 for $\delta^{13}C$–$\delta^{34}S$; and SEAb = 2.214 for $\delta^{34}S$–$\delta^{15}N$). In contrast, February and April showed substantially narrower and comparable niche areas (Table 2 and Fig. 2) indicating reduced isotopic niche width later in the non-breeding season. No isotopic niche overlap was detected between December and either February or April for any isotope combination (SEAc overlap = 0). A partial niche overlap was observed between February and April across all isotopic combinations, with the highest overlap in the $\delta^{34}S$–$\delta^{15}N$ space (overlap area = 0.126) corresponding to 60.9% of February niche and 50.2% of April niche, followed by $\delta^{13}C$–$\delta^{34}S$ (overlap area = 0.085; 53.9% and 48.7%, respectively) and $\delta^{13}C$–$\delta^{15}N$ (overlap area = 0.07; 49.8% and 39.1%, respectively) (Fig. 2).

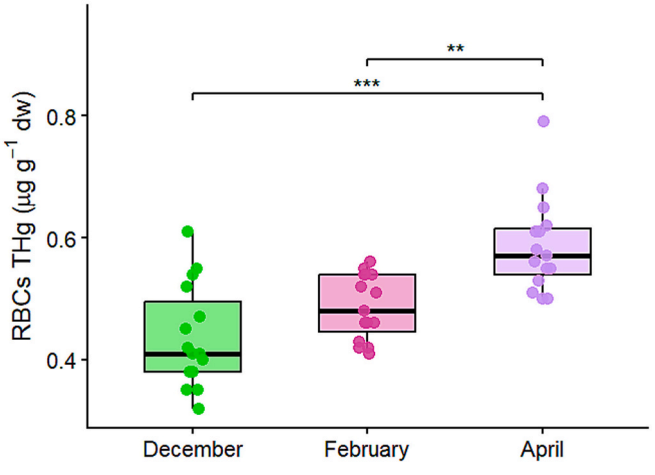


Fig. 1. Blood THg concentrations (THg, μg g^{-1} dw) in Common terns (*Sterna hirundo*) during the different months of the non-breeding season at Punta Rasa, Bahía Samborombón, Buenos Aires Province. Asterisks indicate significant pairwise differences (**$p < 0.01$; ***$p < 0.001$).

Blood THg concentrations were positively associated with $\delta^{34}S$ (est = 0.0496, SE = 0.0208, $t_{41} = 2.39$, $p = 0.0216$), whereas a negative association was observed with $\delta^{15}N$ (est = −0.0514, SE = 0.0143, $t_{41} = -3.60$, $p = 0.0008$). The association between THg and $\delta^{13}C$ was positive but did not reach statistical significance (est = 0.0604, SE = 0.0325, $t_{41} = 1.86$, $p = 0.0706$; Fig. 3) Residual diagnostics indicated no evidence of heterogeneity of variance among sampling months (Fligner–Killeen tests, all $p > 0.57$) and, the residuals were approximately normally distributed for the $\delta^{13}C$ and $\delta^{34}S$ models (Shapiro–Wilk tests, $p = 0.077$ and 0.114, respectively). Conversely, the $\delta^{15}N$ model showed a deviation from normality (Shapiro-Wilk, W = 0.931, $p = 0.010$; Supplementary material, table S1).

3.3. Blood THg concentrations and physiological parameters

Several physiological parameters showed seasonal variation throughout the non-breeding period (Table 2). Body mass showed a seasonal pattern, with the lowest values in February and the highest in April (February–April contrast: est. = −12.28, SE = 3.77, $t_{41} = -3.26$, Tukey-adjusted $p = 0.006$). Triacylglycerol concentrations were higher in April than in December (est = 0.755, SE = 0.128, $p < 0.0001$) and February (February–April contrast: est. = −0.556 m SE = 0.120, Tukey-adjusted $p = 0.0001$). The difference between December and February was not significant (Tukey-adjusted $p = 0.171$). Cholesterol concentrations were higher in April than in December (Tukey-adjusted $p = 0.0288$), whereas the December–February and February–April comparisons were not significant ($p = 0.0873$ and 0.5431, respectively). No significant monthly differences were detected for total proteins, albumin, uric acid, glucose, or IgY (Supplementary material, table S2;S3).

Regarding their associations with blood THg, triacylglycerol and acid uric concentrations showed a marginal negative association with THg that did not reach statistical significance (est = −1.123, SE = 0.593, $t_{39} = -1.90$, $p = 0.065$; est. = −13.10, SE = 6.69, $t_{39} = -1.96$, $p = 0.058$, respectively). No significant associations with THg were detected for body mass, cholesterol, albumin, glucose or IgY (all $p > 0.05$) (Supplementary material, table S2).

4. Discussion

4.1. Seasonal variation in mercury contamination and feeding ecology

In this study, blood THg concentrations in Common terns ranged from 0.32 to 0.80 μg g^{-1} dw (equivalent to 0.07–0.17 μg g^{-1} wet weight [ww], assuming a mean moisture content of 79%; Ackerman et al., 2016). These concentrations were low compared with those reported for other breeding populations of the same species and other terns. For instance, adult Common terns breeding in North American freshwater lakes showed blood THg concentrations of 0.92–1.45 μg g^{-1} ww in males and 0.67–1.03 μg g^{-1} ww in females (Bracey, 2021), whereas, concentrations in a breeding population from Germany ranged from 0.29 to 3.90 μg g^{-1} ww (Bertram et al., 2024). Foster's terns, a closely related species breeding in California exhibited blood concentrations of 1.09 ± 0.89 μg g^{-1} ww (Ackerman et al., 2008). According to published avian blood-mercury benchmarks (Ackerman et al., 2016), the concentrations measured in our study were at or below the boundary between background and low-risk exposure and well below the 1.0 μg g^{-1} ww benchmark for moderate risk. However, the more recent toxicity reference proposed by Ackerman et al. (2024) suggests that low-level biological effects remain possible. Although blood THg concentrations were relatively low compared with other populations, their toxicological significance should be interpreted cautiously because MeHg was not measured directly and its proportion of blood THg in our samples

Table 1
Blood THg concentrations (THg, μg g^{-1} dw) and stable isotopes values of $\delta^{13}C$ (‰, Vienna Pee Dee Belemnite), $\delta^{15}N$ (‰, air) and $\delta^{34}S$ (‰, Vienna Canyon Diablo Troilite) (Mean ± SD [min-max]) in Common terns (*Sterna hirundo*) during the different months of the non-breeding season at Punta Rasa, Bahía Samborombón, Buenos Aires province. Standard ellipse areas corrected for small sample size (SEAc, $‰^2$) and the mode and 95% credible intervals for Bayesian standard ellipse areas (SEAb, $‰^2$) are shown.

	December	February	April
THg	0.44 ± 0.08 [0.32–0.62]	0.49 ± 0.05 [0.42–0.56]	0.59 ± 0.07 [0.50–0.80]
$\delta^{13}C$ ‰	−19 ± 0.51 [−18.08 - −19.59]	−17.85 ± 0.18 [−17.51 - −18.21]	−17.74 ± 0.19 [−17.47 - −18.07]
$\delta^{15}N$ ‰	14.14 ± 1.15 [11.11–15.23]	16 ± 0.24 [15.63–16.54]	16.14 ± 0.26 [15.45–16.57]
$\delta^{34}S$ ‰	17.53 ± 0.80 [16.59–19.18]	18.70 ± 0.25 [18.20–19.05]	18.63 ± 0.28 [17.89–19.01]
SEAc $\delta^{13}C$–$\delta^{15}N$ $‰^2$	1.128	0.140	0.178
SEAc $\delta^{13}C$–$\delta^{34}S$ $‰^2$	0.408	0.157	0.174
SEAc $\delta^{34}S$-$\delta^{15}N$ $‰^2$	2.018	0.207	0.251
SEAb $\delta^{13}C$–$\delta^{15}N$ $‰^2$	1.264 [0.783–2.216]	0.135 [0.084–0.237]	0.169 [0.108–0.294]
SEAb $\delta^{13}C$–$\delta^{34}S$ $‰^2$	0.602 [0.377–1.030]	0.150 [0.094–0.263]	0.167 [0.106–0.286]
SEAb $\delta^{34}S$-$\delta^{15}N$ $‰^2$	2.069 [1.287–3.600]	0.196 [0.125–0.344]	0.241 [0.149–0.422]

Table 2
Serum hematological markers of Common terns (*Sterna hirundo*) during the non-breeding season in Punta Rasa, Bahía Samborombón, Buenos Aires province. Total proteins (g/dl), triacylglycerol (mg/dl), Uric acid (mg/dl), cholesterol (mg/dl), albumin (g/dl), glucose (mg/dl) and IgY (OD 405 nm) and body mass (g).

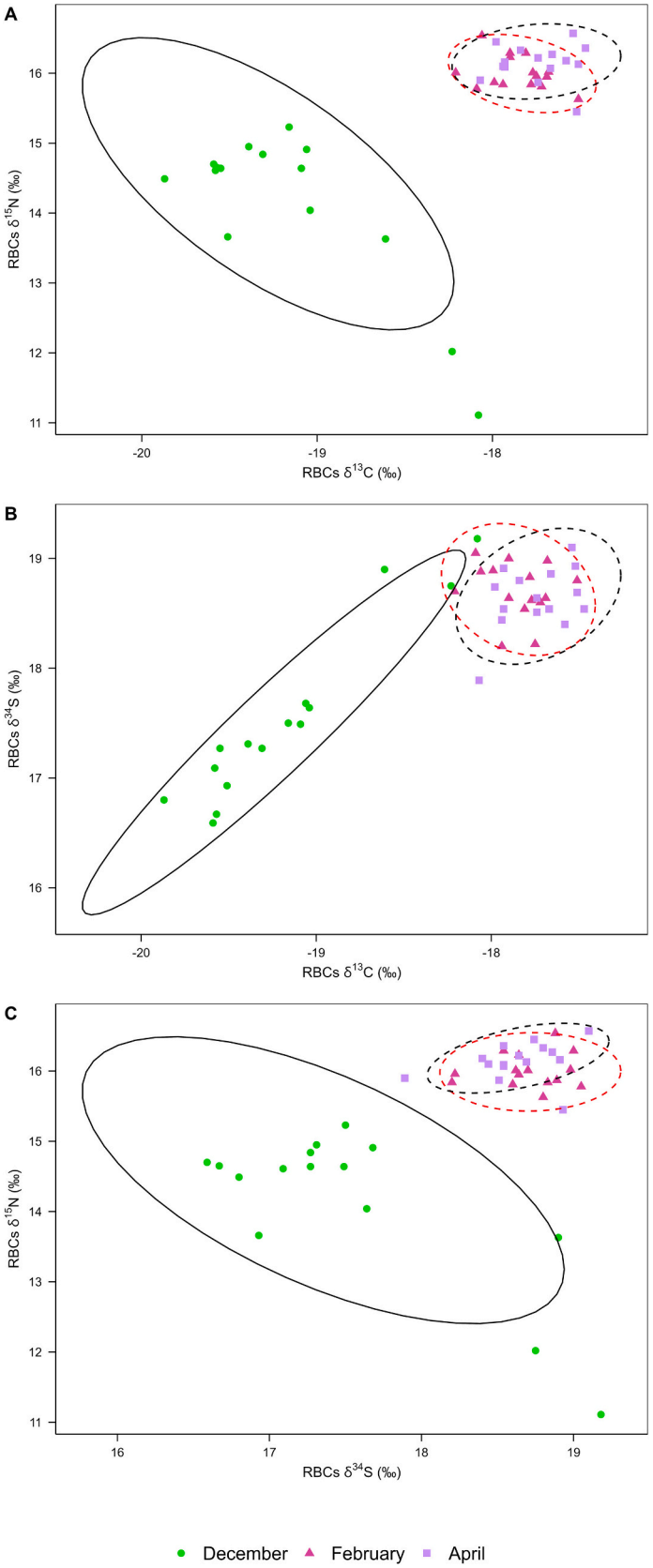
Month / Parameters	December	February	April
	Mean ± SD [Min – Max]	Mean ± SD [Min – Max]	Mean ± SD [Min – Max]
Total proteins (g/dl)	3.28 ± 0.40 [2.5–4.3]	3.45 ± 0.51 [2.5–4.3]	3.40 ± 0.27 [3.0–3.8]
Triacylglicerols (mg/dl)	99.73 ± 25.56 [54–146]	116.28 ± 37.68 [66–208]	181.28 ± 57.99 [121–324]
Uric acid (mg/dl)	9.73 ± 3.59 [6.22–19.39]	9.83 ± 3.75 [4.84–17.68]	8.33 ± 2.19 [5.52–13.44]
Cholesterol (mg/dl)	285.47 ± 33.49 [237.36–344.62]	321.36 ± 78.23 [176.07–455.2]	326.78 ± 48.75 [245.31–390.79]
Albumin (g/dl)	1.31 ± 0.17 [1.04–1.68]	1.37 ± 0.31 [0.62–1.76]	1.45 ± 0.13 [1.25–1.72]
Glucose (mg/dl)	397 ± 41.67 [326–469]	419 ± 72 [278–517]	390 ± 30 [341–427]
IgY (OD 405 nm)	0.21 ± 0.12 [0.05–0.52]	0.19 ± 0.05 [0,095–0,28]	0.24 ± 0.07 [0.13–0.35]
Body mass (g)	129.41 ± 7.47 [118.10–142.10]	123.30 ± 4.87 [114.7–130.9]	136.91 ± 12.49 [114–165.3]

remains unknown. Furthermore, differences among populations may reflect geographical variations in Hg availability, resource use and stage of the annual cycle (Bracey, 2021; Mills et al., 2022), highlighting the role of local ecological conditions in shaping Hg exposure. Because published blood Hg data for Common terns and other seabirds are largely derived from breeding populations, comparisons with the present study should be interpreted in the context of differences in sampling period and ecological conditions. During the non-breeding period, migratory seabirds may occupy geographically distinct habitats and exploit different food resources, potentially leading to variation in Hg exposure and accumulation. By documenting blood Hg concentrations in Common terns during the non-breeding period, this study complements existing information from breeding populations and contributes to a more comprehensive understanding of Hg exposure across the annual cycle. Blood Hg concentrations may vary with age and sex in seabirds. In Common terns blood Hg concentrations have been reported to increase with age (Bertram et al., 2024), although age-related patterns may also vary among species and may be influenced by differences in diet, moult, and Hg accumulation and elimination (Tavares et al., 2013; Tartu et al., 2014; Bustamante et al., 2016). Sex-related differences may reflect variation in Hg accumulation and elimination processes, for instance the transfer of Hg to eggs during laying in females (Bertram et al., 2024). Because the age and sex of the individuals sampled in the present study could not be determined, the potential influence of these factors on blood THg concentrations could not be assessed.

Blood THg concentrations increased significantly from December, early in the non-breeding season, to April, the pre-migration period, and were also significantly higher in April than in February, whereas concentrations did not differ significantly between December and February (Fig. 1). Raw arithmetic mean THg concentrations increased by approximately 34% from December to April (Table 1). These seasonal patterns may reflect changes in Hg exposure during the non-breeding period, although other processes could also contribute to temporal variation in circulating Hg. The non-breeding period encompasses the moult of primary and secondary flight feathers in Common terns (Nisbet, 2017), which may contribute to Hg elimination through deposition into growing feathers (Furness et al., 1986; Albert et al., 2019). Thus, moult may represent an additional source of temporal variation in circulating THg during this period. Common terns at Punta Rasa reach their maximum primary-feather moult index between January and April (*unpublished results*), suggesting that the progression of moult may contribute to seasonal variation in circulating THg. However, moult stage was not recorded in the individuals sampled in this study, preventing us from assessing its potential influence on blood THg concentrations.

The temporal variation in THg concentrations was accompanied by changes in stable isotope values, with $\delta^{13}C$, $\delta^{34}S$ and $\delta^{15}N$ increasing by approximately 7.5, 6.0 and 14.2%, respectively. However, the seasonal trajectories differed: $\delta^{13}C$ and $\delta^{15}N$ showed relatively consistent enrichment across the sampling period, whereas $\delta^{34}S$ increased markedly between December and February and remained at similarly enriched values in April. The coinciding variation in THg and stable isotopes suggests that seasonal changes in feeding ecology may contribute to the observed variation in Hg contamination. Nevertheless, these population-level patterns should not necessarily be interpreted as within-individual shifts in foraging habitat, because each bird was sampled only once and therefore seasonal variation may also reflect differences among individuals in migratory history, arrival timing, previous feeding areas, or other ecological characteristics.

Common terns migrating to South America during the non-breeding season originate from breeding colonies in North America and use multiple stopover sites along the Atlantic coast (Neves et al., 2015; Nisbet, 2017). Thus, blood THg concentrations and isotopic values measured early in the non-breeding season (December) may partly reflect contamination and dietary inputs acquired prior to arrival, whereas later samples may increasingly reflect local feeding conditions as tissue turnover occurs. The overall enrichment of $\delta^{13}C$ and $\delta^{34}S$ from December to April (Table 1) suggests seasonal changes in the isotopic composition of assimilated resources. However, these changes may reflect shifts in dietary sources, temporal variation in isotopic baselines, or a combination of both. December also showed greater variability in $\delta^{34}S$ and the widest isotopic niche, whereas February and April exhibited narrower and more comparable niche areas, with partial overlap



(caption on next page)

Fig. 2. Trophic ecology of Common Terns (*Sterna hirundo*) during the non-breeding season at Punta Rasa, Bahía Samborombón, Buenos Aires province. **(A)** Biplot of stable isotope values of carbon (δ^{13}C; ‰, Vienna Pee Dee Belemnite) and nitrogen (δ^{15}N; ‰, air) in red blood cells of individuals sampled in December (green), February (pink), and April (purple). **(B)** Biplot of stable isotopes of carbon (δ^{13}C; ‰, Vienna Pee Dee Belemnite) and sulfur (δ^{34}S; ‰, Vienna Canyon Diablo Troilite) in red blood cells. **(C)** Biplot of stable isotopes of sulfur (δ^{34}S; ‰, Vienna Canyon Diablo Troilite) and nitrogen (δ^{15}N; ‰, air) in red blood cells. Standard Ellipse Areas corrected for small sample size (SEAc) for each month (December: solid line; February: red dotted line and April: black dotted line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

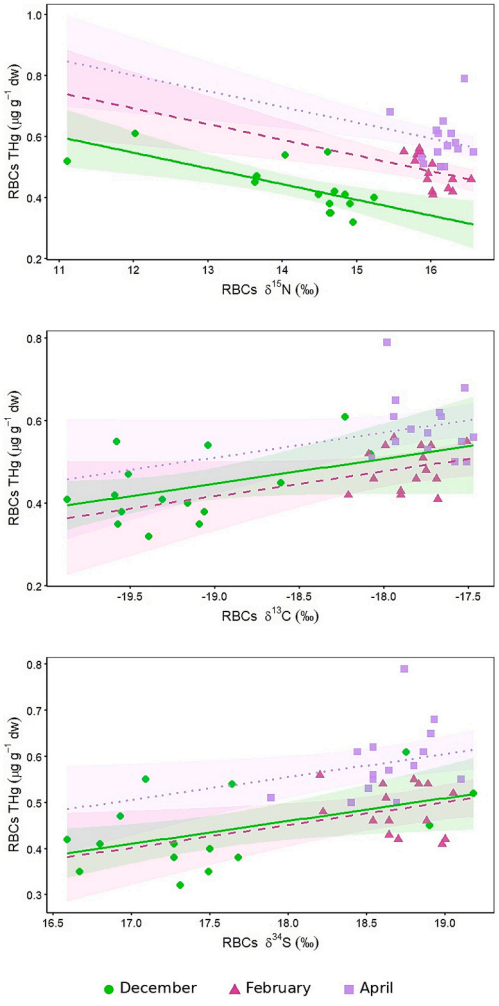


Fig. 3. Relationships between blood THg (μg g^{-1} dw) and stable isotope values of δ^{15}N, δ^{13}C and δ^{34}S (‰) in Common terns during the non-breeding season at Punta Rasa, Bahía Samborombón, Buenos Aires province. Points represent birds sampled in December (green circles), February (pink triangles), and April (purple squares). Lines represent model-predicted relationships from separate additive linear models for each isotope, including isotope values and sampling month as predictors. Shaded areas indicate 95% confidence intervals. The models account for seasonal variation in blood THg concentrations while estimating the association between THg and each isotope. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between these two periods. The broader isotopic niche observed in December suggests greater heterogeneity in feeding ecology at the beginning of the non-breeding season (Fig. 2), whereas the narrower niches observed later in the season are consistent with greater similarity among individuals in their isotopic composition.

Another plausible explanation for the temporal variation in feeding ecology and blood THg concentrations is related to the seasonal movements and ontogenetic habitat shifts of the Argentine anchovy (*Engraulis anchoita*), the main prey for Common terns at Punta Rasa (Mauco and Favero, 2005; Carrillo et al., 2025). Argentine anchovy occurs in estuarine and shallow coastal nursery areas during its early life stages and progressively occupies coastal and neritic waters as individuals grow (Angelescu, 1982; Sanchez and de Ciechomski, 1995; Hansen and Madirolas, 1996). These ontogenetic shifts, together with changes in prey size and distribution, could influence the resource available to Common terns and, consequently, their Hg exposure. Larger and older fish may accumulate higher Hg concentrations (Carr et al., 2017), and changes in the availability or consumption of prey of different sizes could therefore contribute to seasonal variation in Hg contamination (Choy et al., 2009). However, prey size, Hg concentrations in anchovy, and seasonal changes in prey availability were not directly assessed in the present study, and this mechanism should therefore be considered a plausible ecological hypothesis rather than a demonstrated pathway.

The positive association between blood THg concentrations and δ^{34}S values, together with the positive but weaker associations with δ^{13}C, suggest that variation in isotopic composition may be related to differences in Hg exposure (Fig. 3). After accounting for month, individuals with more enriched δ^{34}S values tended to have higher blood THg concentrations, whereas the positive association with δ^{13}C did not reach statistical significance. The broader isotopic niche observed in December, together with the narrower niches observed in February and April, suggests greater among-individual heterogeneity in feeding ecology early in the non-breeding season and greater similarity among individuals later in the season (Fig. 2). This pattern may indicate a reduction in among-individual heterogeneity in feeding ecology over the non-breeding period, although the mechanisms underlying this pattern cannot be determined from the present data. Because each bird was sampled only once, these seasonal patterns cannot be interpreted as evidence of within-individual changes in foraging ecology.

A seasonal increase in δ^{15}N values was also observed, whereas blood THg concentrations showed a significant negative association with δ^{15}N values after accounting for month (Fig. 3). This negative relationship contrasts with the positive association between trophic position and Hg exposure commonly expected from biomagnification. However, δ^{15}N is influenced not only by trophic position but also by baseline isotopic variation, which can be substantial in estuarine and coastal systems due to spatial and temporal differences in nitrogen sources and biogeochemical processes (Post, 2002; Mancinelli et al., 2013). This is particularly relevant at Punta Rasa, where the influence of the Rio de La Plata estuarine waters and multiple organic matter sources contribute to spatial variation in food webs isotopic composition (Botto et al., 2011; Llamazares Vegh et al., 2021). Consequently, the seasonal enrichment in δ^{15}N observed in Common terns may reflect changes in trophic position, prey composition, baseline isotopic values, or a combination of these processes. In the absence of isotopic data for potential prey and baseline organisms, their relative contributions cannot be determined. Indeed, the negative association between δ^{15}N and blood THg should not necessarily be interpreted as evidence of lower Hg exposure at higher trophic positions but may instead reflect trophic dilution of Hg (Trevizani et al., 2021), and variation in isotopic baselines (Linhares et al., 2026) as reported for estuarine systems. The positive association between δ^{34}S and THg further suggests that differences in feeding habitat or resource use may also contribute to Hg exposure (Linhares et al., 2026). Together, these patterns suggest that the relationship between isotopic composition and Hg exposure in this estuarine system is complex and cannot be fully explained by trophic position alone.

4.2. Physiological markers and Hg contamination

Several physiological markers showed variation across the non-breeding season, although the patterns differed among variables. Triacylglycerol concentrations increased toward April, and body mass was higher in April than in February. Cholesterol concentrations were also higher in April than in December, whereas evidence for seasonal variation in albumin was limited. In contrast, glucose, total proteins, uric acid or IgY did not show significant seasonal variation. Seasonal variation in circulating lipid metabolites has been reported in migratory birds and may reflect changes in energy acquisition, storage, and mobilization associated with different stages of the annual cycle (Jenni-Eiermann and Jenni, 1994; McWilliams et al., 2004). In particular, seasonal changes in circulating triacylglycerols may reflect variation in lipid metabolism and nutritional state, although their interpretation requires consideration of recent food intake and other metabolic processes (Bauch et al., 2010; Jenni-Eiermann and Jenni, 2025).

In this study, blood THg concentrations showed limited associations with physiological parameters. Triacylglycerol and uric acid concentrations showed negative trends with increasing THg concentrations, whereas did not reach statistical significance. Body mass, albumin, glucose, total proteins and IgY were not significantly associated with THg concentrations. The negative association between THg and triacylglycerols is of particular interest because lipid metabolism plays a central role in energy storage and mobilization in migratory birds, and experimental studies have shown that methylmercury exposure can disrupt lipid metabolic pathways in migratory songbirds (Seewagen et al., 2022). However, the observational design of the present study does not allow us to determine whether the negative association reflects a direct effect of Hg on lipid metabolism or variation in other factors affecting energy balance and recent food intake. Furthermore, the relatively small sample size, partly reflecting practical constraints of field sampling, may have limited statistical power to detect associations between THg and physiological parameters. Therefore, non-significant results, particularly where trends were observed, should be interpreted cautiously and do not necessarily indicate an absence of biological effects.

The negative association between THg concentrations and uric acid was weak and did not reach statistical significance. This relationship may nevertheless warrant further investigation given the role of uric acid in antioxidant defence in birds, including the scavenging of reactive oxygen species and the contribution to erythrocyte antioxidant capacity (Ames, 1981; Durante et al., 2010; Liu et al., 2019; Renedo et al., 2021; Ahmad et al., 2022). The observed pattern could be consistent with alterations in oxidative balance under Hg exposure, although alternative mechanisms, including changes in hepatic function and purine metabolism, cannot be excluded (Xu et al., 2022; Ibañez et al., 2024). However, because oxidative stress and antioxidant capacity were not directly measured in the present study, this interpretation remains speculative. Given the limited statistical support for these relationships, these interpretations should be considered exploratory rather than evidence of direct toxicological effects of Hg.

5. Conclusions

This study provides new insight into the trophic ecology and Hg exposure of Common terns (*Sterna hirundo*) during the non-breeding season. The integration of stable isotope values ($\delta^{13}C$, $\delta^{34}S$, and $\delta^{15}N$), blood THg concentrations, and physiological parameters revealed seasonal variation in Hg exposure and isotopic composition, together with limited evidence of associations between Hg concentrations and physiological status. Blood THg concentrations increased toward the pre-migratory period, while the negative association with triacylglycerols suggests a potential relationship between Hg exposure and lipid metabolism. However, these findings should be interpreted cautiously in light of the observational study design and limited sample size. Moreover, this study provides baseline data for long-term biomonitoring at Punta Rasa, an important site for migratory seabirds and shorebirds, and highlights the value of an integrated approach to assessing Hg exposure. These findings provide a basis for future assessments of Hg exposure levels across other bird species using Punta Rasa throughout their annual cycles, helping to characterize interspecific variation in exposure and inform broader wetland conservation efforts and the objectives of the Minamata Convention on Mercury. Further research incorporating prey and isotopic baseline data, together with selenium measurements across multiple non-breeding seasons, is needed to better characterize the ecological drivers of Hg exposure and improve our understanding of its potential biological consequences.

CRediT authorship contribution statement

M.S. Carrillo: Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **D.I. Archuby:** Writing – original draft, Resources, Methodology, Investigation. **P. Bustamante:** Writing – original draft, Methodology, Investigation, Formal analysis. **G. Castresana:** Methodology, Investigation. **M. Lunardelli:** Methodology, Investigation. **B. D'astek:** Investigation. **D. Montalti:** Writing – original draft, Investigation. **A.E. Ibañez:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, 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.

Acknowledgements

The authors are grateful to Ministerio de Ambiente de la Provincia de Buenos Aires (MAPBA) for providing the resources and fieldwork permits to conduct the research; to all park ranger staff from MAPBA Juan Ordoñez, Pablo Rojas, Paola Russo and Mariano Gonzalez for providing the logistic support during bird capture and sample collection at Reserva Natural de Objetivo Definido Rincón de Ajó, Punta Rasa, Bahía Samborombón (Buenos Aires). Thanks to the Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT) for the financial support of this project (PICT-2021-533 to AEI) and The Waterbirds Society (Nisbet Grant to AEI and MSC). We are also grateful to Maud Brault-Favrou from the platform " Analyses Elémentaires" and to Gael Guillou from the platform "Analyses Isotopiques" of LIENSs for their support during Hg and stable isotope analyses, respectively. We thank the CPER (Contrat de Plan Etat-Région) and the FEDER (Fonds Européen de Développement Régional) for funding the AMA and IR-MS of LIENSs laboratory. Micaela Soledad Carrillo is a Doctoral Student at Ornithology Section, Div. Zool. Vertebrates Museo de La Plata (FCNyM-UNLP) and was supported by a CONICET Doctoral Fellowship. We also thank the Editor and Reviewers for their valuable comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.120572.

Data availability

Data will be made available on request.

References

Ackerman, J.T., Eagles-Smith, C.A., Herzog, M.P., Hartman, C.A., 2016. Maternal transfer of contaminants in birds: mercury and selenium concentrations in parents

and their eggs. Environ. Pollut. 210, 145–154. https://doi.org/10.1016/j.envpol.2015.12.016.
Ackerman, J.T., Eagles-Smith, C.A., Takekawa, J.Y., Bluso, J.D., Adelsbach, T.L., 2008. Mercury concentrations in blood and feathers of prebreeding Forster's terns in relation to space use of San Francisco Bay, California, USA, habitats. Environ. Toxicol. Chem. 27 (4), 897. https://doi.org/10.1897/07-230.
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. 43 (6), 1195–1241. https://doi.org/10.1002/etc.5858.
Ahmad, S., Tufail, N., Parveen, N., Mahmood, R., 2022. Attenuation of hg(II)-induced cellular and DNA damage in human blood cells by uric acid. Biochem. Cell Biol. 100 (1), 45–58. https://doi.org/10.1139/bcb-2021-0229.
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.
Ames, B., 1981. Uric acid provides an antioxidant defense in humans against oxidant and radical caused aging and cancer: a hypothesis. Proc. Natl. Acad. Sci. USA 78, 6858–6862, 1981.
Angelescu, V., 1982. Ecología trófica de la anchoíta del mar argentino (engraulidae, *Engraulis anchoita*) parte II. In: Alimentación, comportamiento y relaciones tróficas en el ecosistema. ISSN 0325-6790.
Atwell, L., Hobson, K.A., Welch, H.E., 1998. Biomagnification and bioaccumulation of mercury in an arctic marine food web: insights from stable nitrogen isotope analysis. Can. J. Fish. Aquat. Sci. 55 (5), 1114–1121. https://doi.org/10.1139/f98-001.
Bargagli, R., 2008. Environmental contamination in Antarctic ecosystems. Sci. Total Environ. 400 (1–3), 212–226. https://doi.org/10.1016/j.scitotenv.2008.06.062.
Bauch, C., Kreutzer, S., Becker, P.H., 2010. Breeding experience affects condition: blood metabolite levels over the course of incubation in a seabird. J. Comp. Physiol. B. 180 (6), 835–845. https://doi.org/10.1007/s00360-010-0453-2.
Bearhop, S., Ruxton, G.D., Furness, R.W., 2000. Dynamics of mercury in blood and feathers of great skuas. Environ. Toxicol. Chem. 19 (6), 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 (5), 451–458. https://doi.org/10.1086/342800.
Bertram, J., Bichet, C., Moiron, M., Schupp, P.J., Bouwhuis, S., 2024. Sex- and age-specific mercury accumulation in a long-lived seabird. Sci. Total Environ. 927, 172330. https://doi.org/10.1016/j.scitotenv.2024.172330.
Bertram, J., Kürten, N., Bichet, C., Schupp, P.J., Bouwhuis, S., 2022. Mercury contamination level is repeatable and predicted by wintering area in a long-distance migratory seabird. Environ. Pollut. 313, 120107. https://doi.org/10.1016/j.envpol.2022.120107.
Bond, A.L., 2010. Relationships between stable isotopes and metal contaminants in feathers are spurious and biologically uninformative. Environ. Pollut. 158 (5), 1182–1184. https://doi.org/10.1016/j.envpol.2010.01.004.
Bond, A.L., Diamond, A.W., 2011. Recent bayesian stable-isotope mixing models are highly sensitive to variation in discrimination factors. Ecol. Appl. 21 (4), 1017–1023. https://doi.org/10.1890/09-2409.1.
Bond, A.L., Robertson, G.J., 2015. Mercury concentrations in multiple tissues of arctic Iceland gulls (*Larus glaucoides*) wintering in Newfoundland. Arctic Science 1 (1), 1–8. https://doi.org/10.1139/as-2015-0004.
Botto, F., Gaitán, E., Mianzan, H., Acha, M., Giberto, D., Schiariti, A., Iribarne, O., 2011. Origin of resources and trophic pathways in a large SW Atlantic estuary: an evaluation using stable isotopes. Estuar. Coast. Shelf Sci. 92 (1), 70–77. https://doi.org/10.1016/j.ecss.2010.12.014.
Bracey, A.M., 2021. Ecology and Conservation of Common Terns (*Sterna hirundo*) Breeding in the North American Great Lakes Region. Doctoral dissertation, University of Minnesota.
Burger, J., Gochfeld, M., 2004. Marine birds as sentinels of environmental pollution. EcoHealth 1 (3). https://doi.org/10.1007/s10393-004-0096-4.
Bustamante, P., Carravieri, A., Goutte, A., Barbraud, C., Delord, K., Chastel, O., Cherel, Y., 2016. High feather mercury concentrations in the wandering albatross are related to sex, breeding status and trophic ecology with no demographic consequences. Environ. Res. 144, 1–10. https://doi.org/10.1016/j.envres.2015.10.024.
Bustnes, J.O., Tveraa, T., Varpe, Ø., Henden, J.A., Skaare, J.U., 2007. Reproductive performance and organochlorine pollutants in an Antarctic marine top predator: the south polar skua. Environ. Int. 33 (7), 911–918. https://doi.org/10.1016/j.envint.2007.04.010.
Caldwell, A., Yakola, K., Craig, E., Loring, P., Welch, L., Lyons, D.E., Furey, N.B., 2025. High-resolution satellite telemetry data reveal full migration cycle of gulf of Maine-breeding common terns (*Sterna hirundo*). Waterbirds 48 (3). https://doi.org/10.1675/063.048.0301.
Carr, M.K., Jardine, T.D., Doig, L.E., Jones, P.D., Bharadwaj, L., Tendler, B., Lindenschmidt, K.-E., 2017. Stable sulfur isotopes identify habitat-specific foraging and mercury exposure in a highly mobile fish community. Sci. Total Environ. 586, 338–346. https://doi.org/10.1016/j.scitotenv.2017.02.013.
Carravieri, A., Lorioux, S., Angelier, F., Chastel, O., Albert, C., Bråthen, V.S., 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.
Carravieri, A., Vincze, O., Bustamante, P., Ackerman, J.T., Adams, E.M., Angelier, F., Fort, J., 2022. Quantitative meta-analysis reveals no association between mercury contamination and body condition in birds. Biol. Rev. 97 (4), 1253–1271. https://doi.org/10.1111/brv.12840.
Carrillo, M.S., Archuby, D.I., Castresana, G., Lunardelli, M., Montalti, D., Ibañez, A.E., 2023. Microplastic ingestion by common terns (*Sterna hirundo*) and their prey during the non-breeding season. Environ. Pollut. 327, 121627. https://doi.org/10.1016/j.envpol.2023.121627.
Carrillo, M.S., Archuby, D.I., Lunardelli, M., Castresana, G., Montalti, D., Ibañez, A.E., 2025. Dynamics of microplastic transfer through the food web in a migratory seabird. Environ. Pollut. 383, 126784. https://doi.org/10.1016/j.envpol.2025.126784.
Cathalot, C., Rabouille, C., Tisnérat-Laborde, N., Toussaint, F., Kerhervé, P., Buscail, R., Tesi, T., 2013. The fate of river organic carbon in coastal areas: a study in the Rhône River delta using multiple isotopic ($\delta^{13}C$, $\delta^{14}C$) and organic tracers. Geochim. Cosmochim. Acta 118, 33–55. https://doi.org/10.1016/j.gca.2013.05.001.
Ceyca, J.P., Castillo-Guerrero, J.A., García-Hernández, J., Fernández, G., Betancourt-Lozano, M., 2016. Local and interannual variations in mercury and cadmium in eggs of eight seabird species of the Sinaloa coast, México. Environ. Toxicol. Chem. 35 (9), 2330–2338. https://doi.org/10.1002/etc.3402.
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.
Choy, C.A., Popp, B.N., Kaneko, J.J., Drazen, J.C., 2009. The influence of depth on mercury levels in pelagic fishes and their prey. Proc. Natl. Acad. Sci. 106 (33), 13865–13869. https://doi.org/10.1073/pnas.0900711106.
Coplen, T.B., 2011. Guidelines and recommended terms for expression of stable-isotope-ratio and gas-ratio measurement results. Rapid Commun. Mass Spectrom. 25 (17), 2538–2560.
Corsolini, S., 2009. Industrial contaminants in Antarctic biota. J. Chromatogr. A 1216 (3), 598–612. https://doi.org/10.1016/j.chroma.2008.08.012.
Cossa, D., Tabard, A.-M., 2020. Mercury in marine mussels from the St. Lawrence estuary and gulf (Canada): a mussel watch survey revisited after 40 years. Appl. Sci. 10 (21), 7556. https://doi.org/10.3390/app10217556.
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 (10), 4967–4983. https://doi.org/10.1021/es305071v.
Durante, P., Romero, F., Pérez, M., Chávez, M., Parra, G., 2010. Effect of uric acid on nephrotoxicity induced by mercuric chloride in rats. Toxicol. Ind. Health 26 (3), 163–174. https://doi.org/10.1177/0748233710362377.
Fitzgerald, W.F., Lamborg, C.H., Hammerschmidt, C.R., 2007. Marine biogeochemical cycling of mercury. Chem. Rev. 107 (2), 641–662. https://doi.org/10.1021/cr050353m.
Fleishman, A.B., Orben, R.A., Kokubun, N., Will, A., Paredes, R., Ackerman, J.T., Shaffer, S.A., 2019. Wintering in the western subarctic Pacific increases mercury contamination of red-legged kittiwakes. Environ. Sci. Technol. 53 (22), 13398–13407. https://doi.org/10.1021/acs.est.9b03421.
Fort, J., Lacoue-Labarthe, T., Nguyen, H.L., Boué, A., Spitz, J., Bustamante, P., 2014. Mercury in wintering seabirds, an aggravating factor to winter wrecks? Sci. Total Environ. 527-528, 448–454. https://doi.org/10.1016/j.scitotenv.2015.05.018.
Fry, B., 2006. Stable Isotope Ecology. Springer New York, New York, NY.
Furness, R.W., Muirhead, S.J., Woodburn, M., 1986. Using bird feathers to measure mercury in the environment: relationships between mercury content and moult. Mar. Pollut. Bull. 17 (1), 27–30. https://doi.org/10.1016/0025-326x(86)90801-5.
Gehrke, P., Sheaves, M., Terry, J., Boseto, D., Ellison, J., Figa, B., Wani, J., 2011. Vulnerability of tropical Pacific Fisheries and aquaculture to climate change. University of Tasmania.
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 (4), 1075–1086. https://doi.org/10.1890/13-1229.1.
Goutte, Aurélie, Barbraud, C., Meillère, A., Carravieri, A., Bustamante, P., Labadie, P., 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 (1787), 20133313. https://doi.org/10.1098/rspb.2013.3313.
Hall, B.D., Aiken, G.R., Krabbenhoft, D.P., Marvin-DiPasquale, M., Swarzenski, C.M., 2008. Wetlands as principal zones of methylmercury production in southern Louisiana and the Gulf of Mexico region. Environ. Pollut. 154 (1), 124–134. https://doi.org/10.1016/j.envpol.2007.12.017.
Hansen, J.E., Madirolas, A., 1996. Distribución, evaluación acústica y estructura poblacional de la anchoíta. Resultados de las campañas del año 1993.
Hobson, K.A., Schell, D.M., Renouf, D., Noseworthy, E., 1996. Stable carbon and nitrogen isotopic fractionation between diet and tissues of captive seals: implications for dietary reconstructions involving marine mammals. Can. J. Fish. Aquat. Sci. 53 (3), 528–533. https://doi.org/10.1139/f95-209.
Hobson, Keith A., Clark, R.G., 1992. Assessing avian diets using stable isotopes I: turnover of13C in tissues. Condor 94 (1), 181–188. https://doi.org/10.2307/1368807.
Ibañez, A.E., Mills, W.F., Bustamante, P., McGill, R.A.R., Morales, L.M., Palacio, F.X., Torres, D.S., Haidr, N.S., Mariano-Jelicich, R., Phillips, R.A., Montalti, D., 2022. Variation in blood mercury concentrations in brown skuas (Stercorarius antarcticus) is related to trophic ecology but not breeding success or adult body condition. Mar. Pollut. Bull. 181, 113919. https://doi.org/10.1016/j.marpolbul.2022.113919.
Ibañez, Andrés E., Mills, W.F., Bustamante, P., Morales, L.M., Torres, D.S., D' Astek, B., Montalti, D., 2024. Deleterious effects of mercury contamination on immunocompetence, liver function and egg volume in an Antarctic seabird. Chemosphere 346, 140630. https://doi.org/10.1016/j.chemosphere.2023.140630.

Jackson, A.L., Inger, R., Parnell, A.C., Bearhop, S., 2011. Comparing isotopic niche widths among and within communities: SIBER - stable isotope bayesian ellipses in R. J. Anim. Ecol. 80 (3), 595–602. https://doi.org/10.1111/j.1365-2656.2011.01806.x.

Jenni-Eiermann, S., Jenni, L., 1994. Plasma metabolite levels predict individual body-mass changes in a small long-distance migrant, the garden warbler. Auk 111 (4), 888–899. https://doi.org/10.2307/4088821.

Jenni-Eiermann, S., Jenni, L., 2025. Migration strategy and diet affect the metabolism of passerine birds during endurance flight. Ecol. Evol. 15 (4). https://doi.org/10.1002/ece3.71299.

Kennish, M.J., 2002. Environmental threats and environmental future of estuaries. Environ. Conserv. 29 (1), 78–107. https://doi.org/10.1017/s0376892902000061.

Kesic, R., Elliott, J.E., Elliott, K.H., Lee, S.L., Maisonneuve, F., 2023. Perfluoroalkyl substances in seabird eggs from Canada's pacific coast: temporal trends (1973–2019) and interspecific patterns. Environ. Sci. Technol. 57 (29), 10792–10803. https://doi.org/10.1021/acs.est.3c02965.

Kiat, Y., Haviv, E., Perlman, Y., Schekler, I., 2026. Connectivity between breeding sites, wintering areas, and migration routes in common terns (*Sterna hirundo*) breeding in the western Palaearctic. Ibis. https://doi.org/10.1111/ibi.70062.

Lamacchia, P., Madrid, E.A., Mariano-Jelicich, R., 2019. Intraspecific variability in isotopic composition of a monomorphic seabird, the common tern (*Sterna hirundo*) at wintering grounds. Emu Austral Ornithol. 119 (2), 176–185. https://doi.org/10.1080/01584197.2019.1580536.

Lambertsson, L., Nilsson, M., 2006. Organic material: the primary control on mercury methylation and ambient methyl mercury concentrations in estuarine sediments. Environ. Sci. Technol. 40 (6), 1822–1829. https://doi.org/10.1021/es051785h.

Lamborg, C.H., Hammerschmidt, C.R., Bowman, K.L., Swarr, G.J., Munson, K.M., Ohnemus, D.C., Saito, M.A., 2014. A global ocean inventory of anthropogenic mercury based on water column measurements. Nature 512 (7512), 65–68. https://doi.org/10.1038/nature13563.

Lavoie, R.A., Jardine, T.D., Chumchal, M.M., Kidd, K.A., Campbell, L.M., 2013. Biomagnification of mercury in aquatic food webs: a worldwide meta-analysis. Environ. Sci. Technol. 47 (23), 13385–13394. https://doi.org/10.1021/es403103t.

Linhares, B.A., Bustamante, P., Nunes, G.T., Costa, P.G., Bugoni, L., Zebral, Y.D., Bianchini, A., 2026. Sulfur isotopes reveal spatial variation in waterbird trace element contamination from tropical estuaries to the open ocean. Environ. Sci. Technol. 60 (12), 9508–9520. https://doi.org/10.1021/acs.est.5c14633.

Liu, D., Yun, Y., Yang, D., Hu, X., Dong, X., Zhang, N., Duan, W., 2019. What is the biological function of uric acid? An antioxidant for neural protection or a biomarker for cell death. Dis. Markers 2019, 1–9. https://doi.org/10.1155/2019/4081962.

Liu, M., Zhang, Q., Maavara, T., Liu, S., Wang, X., Raymond, P.A., 2021. Rivers as the largest source of mercury to coastal oceans worldwide. Nat. Geosci. 14 (9), 672–677. https://doi.org/10.1038/s41561-021-00793-2.

Llamazares Vegh, S., Volpedo, A.V., Sánchez, S., Avigliano, E., 2021. Biogeochemical multi-tag approach reveals the habitat use of a large-scale migratory fish through a fluvio-estuarine system. River Res. Appl. 37 (6), 880–888. https://doi.org/10.1002/rra.3797.

Ludwig, S.C., Becker, P.H., 2006. Waiting for the mate? Spatial behaviour of common terns, *Sterna hirundo*, during courtship. Anim. Behav. 72 (5), 1093–1102. https://doi.org/10.1016/j.anbehav.2006.03.013.

Mancinelli, G., Vizzini, S., Mazzola, A., Stefano, M., Basset, A., 2013. Cross-validation of δ15N and FishBase estimates of fish trophic position in a Mediterranean lagoon: the importance of the isotopic baseline. Estuar. Coast. Shelf Sci. 135, 77–85. https://doi.org/10.1016/j.ecss.2013.04.004.

Martínez, J., Tomás, G., Merino, S., Arriero, E., Moreno, J., 2003. Detection of serum immunoglobulins in wild birds by direct ELISA: a methodological study to validate the technique in different species using antichicken antibodies. Funct. Ecol. *17* (5), 700–706. JSTOR. https://doi.org/10.2307/3599166.

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.

Matos, M., Ramos, A., Brandao, A., Bessa, F., Silva, V., Rodrigues, I., Paiva, H., 2023. Seabirds as bioindicators of anthropogenic and chemical pollution. Sci. Lett. https://doi.org/10.48797/sl.2023.58.

Mauco, L., Favero, M., 2005. The food and feeding biology of common terns wintering in Argentina: influence of environmental conditions. Waterbirds *28* (4), 450–457. JSTOR. https://doi.org/10.2307/4132627.

McWilliams, S.R., Guglielmo, C., Pierce, B., Klaassen, M., 2004. Flying, fasting, and feeding in birds during migration: a nutritional and physiological ecology perspective. J. Avian Biol. 35 (5), 377–393. https://doi.org/10.1111/j.0908-8857.2004.03378.x.

Mills, W.F., Buss, D.L., Bustamante, P., Ramírez, F., Forcada, J., Forero, M.G., Phillips, R.A., 2025. Annual trends in mercury contamination are associated with changing trophic niches of giant petrels. Environ. Res. 270, 121010. https://doi.org/10.1016/j.envres.2025.121010.

Mills, W.F., Bustamante, P., McGill, R.A.R., Anderson, O.R.J., Bearhop, S., Cherel, Y., Phillips, R.A., 2020. Mercury exposure in an endangered seabird: long-term changes and relationships with trophic ecology and breeding success. Proc. R. Soc. B Biol. Sci. 287 (1941), 20202683. https://doi.org/10.1098/rspb.2020.2683.

Mills, W.F., Ibañez, A.E., Bustamante, P., Carneiro, A.P.B., Bearhop, S., Cherel, Y., Phillips, R.A., 2022. Spatial and sex differences in mercury contamination of skuas in the Southern Ocean. Environ. Pollut. 297, 118841. https://doi.org/10.1016/j.envpol.2022.118841.

Neves, V.C., Nava, C.P., Cormons, M., Bremer, E., Castresana, G., Lima, P., Santos, R.S., 2015. Migration routes and non-breeding areas of common terns (*Sterna hirundo*) from the Azores. Emu 115 (2), 158–167. https://doi.org/10.1071/mu13112.

Nisbet, I.C.T., 2017. Common terns (*Sterna hirundo*). The Birds of North America Online. https://doi.org/10.2173/bna.618.

Petalas, C., Lacombe, R.M., Elliott, K.H., Lavoie, R.A., 2025. Coastal foraging increases mercury concentrations in a breeding seabird: insights from isotopes, biologging, and prey. Sci. Total Environ. 965, 178660. https://doi.org/10.1016/j.scitotenv.2025.178660.

Peterson, B.J., Fry, B., 1987. Stable isotopes in ecosystem studies. Annu. Rev. Ecol. Syst. 18, 293–320.

Phillips, O.L., Lewis, S.L., 2014. Evaluating the tropical forest carbon sink. Glob. Chang. Biol. 20 (7), 2039–2041. https://doi.org/10.1111/gcb.12423.

Ponton, D.E., Hare, L., 2015. Using sulfur stable isotopes to understand feeding behavior and selenium concentrations in yellow perch (*Perca flavescens*). Environ. Sci. Technol. 49 (13), 7633–7640. https://doi.org/10.1021/acs.est.5b00718.

Popp, B.N., Graham, B.S., Olson, R.J., Hannides, C.C.S., Lott, M.J., López-Ibarra, G.A., Fry, B., 2007. Insight into the trophic ecology of yellowfin tuna, *Thunnus albacares*, from compound-specific nitrogen isotope analysis of proteinaceous amino acids. Terrestrial Ecology 173–190. https://doi.org/10.1016/s1936-7961(07)01012-3.

Post, D., 2002. Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology 83 (3), 703–718. https://doi.org/10.1890/0012-9658(2002)083.

Qiu, X., Liu, M., Zhang, Y., Zhang, Q., Lin, H., Cai, X., Tao, S., 2025. Declines in anthropogenic mercury emissions in the global north and China offset by the global south. *Nat. Commun.* 16 (1). https://doi.org/10.1038/s41467-025-56274-2.

Quillfeldt, P., Cherel, Y., Navarro, J., Phillips, R.A., Masello, J.F., Suazo, C.G., Bustamante, P., 2022. Variation among species and populations, and carry-over effects of winter exposure on mercury accumulation in small petrels. Front. Ecol. Evol. 10. https://doi.org/10.3389/fevo.2022.915199.

R Core Team, 2023. R: A Language and Environment for Statistical Computing. Recuperado de R Foundation for Statistical Computing website. https://www.r-project.org/.

Renedo, M., Amouroux, D., Duval, B., Carravieri, A., Tessier, E., Barre, J., 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 (7), 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.

Roos, P.M., Dencker, L., 2012. Mercury in the spinal cord after inhalation of mercury. Basic Clin. Pharmacol. Toxicol. 111 (2), 126–132.

Sanchez, R.P., Ciechomski, J.D. de, 1995. Spawning and nursery grounds of pelagic fish species in the sea-shelf off Argentina and adjacent areas. Scientia Marina (Espana) 59 (3–4).

Sapoznikow, A., Vila, A., Lopez De Casenave, J., Vuillermoz, P., 2002. Abundance of common terns at Punta Rasa, Argentina; a major wintering area. Waterbirds 25 (3), 378–381.

Seewagen, C.L., Elowe, C.R., Gerson, A.R., Derrick, Ma, Y., Mustafa Yıldırım, Guglielmo, C.G., 2022. Short-term mercury exposure disrupts muscular and hepatic lipid metabolism in a migrant songbird. Sci. Rep. 12 (1). https://doi.org/10.1038/s41598-022-15680-y.

Singer, M.B., Harrison, L.R., Donovan, P.M., Blum, J.D., Marvin-DiPasquale, M., 2016. Hydrologic indicators of hot spots and hot moments of mercury methylation potential along river corridors. Sci. Total Environ. 568, 697–711. https://doi.org/10.1016/j.scitotenv.2016.03.005.

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 (8), 084004. https://doi.org/10.1088/1748-9326/ab281f.

Syväranta, J., Lensu, A., Marjomäki, T.J., Oksanen, S., Jones, R.I., 2013. An empirical evaluation of the utility of convex hull and standard ellipse areas for assessing population niche widths from stable isotope data. PloS One 8 (2), e56094. https://doi.org/10.1371/journal.pone.0056094.

Tan, S.W., Meiller, J.C., Mahaffey, K.R., 2009. The endocrine effects of mercury in humans and wildlife. Crit. Rev. Toxicol. 39 (3), 228–269. https://doi.org/10.1080/10408440802233259.

Tansel, B., 2026. Trophic-level accumulation and transfer of legacy and emerging contaminants in marine biota: meta-analysis of mercury, PCBs, microplastics, PFAS, PAHs. Mar. Pollut. Bull. 222, 118666. https://doi.org/10.1016/j.marpolbul.2025.118666.

Tartu, S., Bustamante, P., Goutte, A., Cherel, Y., Weimerskirch, H., Bustnes, J.O., Chastel, O., 2014. Age-related mercury contamination and relationship with luteinizing hormone in a long-lived Antarctic bird. PloS One 9 (7), e103642. PubMed Central. https://doi.org/10.1371/journal.pone.0103642.

Tartu, S., Goutte, A., Bustamante, P., Angelier, F., Moe, B., Clément-Chastel, C., Chastel, O., 2013. To breed or not to breed: endocrine response to mercury contamination by an arctic seabird. Biol. Lett. 9 (4), 20130317. https://doi.org/10.1098/rsbl.2013.0317.

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.

Trevizani, T.H., Lopes, C., César, M., Domit, C., 2021. Mercury in trophic webs of estuaries in the Southwest Atlantic Ocean. Mar. Pollut. Bull. 167, 112370. https://doi.org/10.1016/j.marpolbul.2021.112370.

Whitney, M.C., Cristol, D.A., 2017. Impacts of sublethal mercury exposure on birds: a detailed review. Rev. Environ. Contam. Toxicol. 244, 113–163. https://doi.org/10.1007/398_2017_4.

Xu, L., Yang, Y., Wen, Y., Jeong, J.-M., Emontzpohl, C., Atkins, C.L., Ju, C., 2022. Hepatic recruitment of eosinophils and their protective function during acute liver injury. J. Hepatol. 77 (2), 344–352. https://doi.org/10.1016/j.jhep.2022.02.024.