Environment International 214 (2026) 110386

Contents lists available at ScienceDirect

Environment International

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

Full length article

Nationwide monitoring of seabirds reveals species- and site-specific legacy PFAS contamination in French coastal areas

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ARTICLE INFO

Keywords:
Pollution
PFCA
PFSA
Plasma
Wildlife
Atlantic
Mediterranean

ABSTRACT

Per- and poly-fluoroalkyl substances (hereafter PFAS) are widespread and persistent compounds that pose a threat to human and wildlife health. Wildlife monitoring is essential to understand the extent of PFAS contamination and its ecological drivers. Seabirds are good bioindicators of PFAS contamination of the marine environment, yet some areas, including the French coastlines, remain poorly covered. Here, we quantified 11 legacy PFAS in the plasma of 9 seabird species (n = 340 chicks) from 30 sites along the French Atlantic and Mediterranean coasts. Linear perfluorooctanesulfonic acid was by far the most abundant PFAS. Oceanic piscivorous species (Northern gannets *Morus bassanus*, black-legged kittiwakes *Rissa tridactyla* and Scopoli's shearwaters *Calonectris diomedea*) had the highest PFAS concentrations compared to *Larus* sp. gulls and shags *Gulosus aristotelis*. Overall, Mediterranean seabirds had lower perfluoroalkyl sulfonic acid and higher perfluoroalkyl carboxylic acid concentrations compared to Atlantic seabirds. At a finer spatial scale, chicks sampled near estuaries had a slightly higher PFAS burden, suggesting local riverine inputs. This first large-scale survey of PFAS in French seabirds reveals substantial heterogeneity in PFAS contamination across French coastal environments. Future work should address the sources of this PFAS contamination and quantify its toxicological consequences, given that sampled chicks may be at risk based on previous avian studies reporting PFAS-related health effects.

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https://doi.org/10.1016/j.envint.2026.110386
Received 24 January 2026; Received in revised form 22 June 2026; Accepted 22 June 2026
Available online 24 June 2026
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1. Introduction

Per- and poly-fluoroalkyl substances (PFAS) are a diverse group of several thousand organofluorine chemicals, with widespread industrial and consumer applications (Gaines, 2023). Due to their proven deleterious effects on human and wildlife (Fenton et al., 2021; Ma et al., 2023; Reiner and Place, 2015), PFAS are an international public health concern, with three legacy PFAS and their related salts (perfluorooctanesulfonic acid, perfluorooctanoic acid, and perfluorohexanesulphonic acid – PFOS, PFOA, and PFHxS, respectively) being regulated under the Stockholm Convention on Persistent Organic Pollutants (POPs) (United Nations, 2020). In the European Union, several PFAS are also included in the European Chemicals Agency's (ECHA, https://echa.europa.eu/candidate-list-table) candidate list of substances of very high concern under the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) (REACH Regulation, 2006). In 2023, a restriction proposal was also submitted to ECHA to ban uses of all PFAS in European countries (ECHA, 2023a), but with potential derogations currently in discussion (ECHA, 2023b).

In Europe, 20 PFAS production plants have been identified, some of which have manufactured legacy PFAS for decades, as well as more than 20,000 sites for which soil, water, or biota have been contaminated (Cordner et al., 2024; Dalmijn et al., 2024; Moghadasi et al., 2023). Considered to be one of the main final sinks for these chemicals, the marine environment is highly contaminated through riverine inputs and atmospheric deposition (González-Gaya et al., 2019; Wang et al., 2025). In Europe, PFAS are found in coastal and oceanic waters and sediments, as well as in the tissues of marine organisms (Boitsov et al., 2024; Brumovský et al., 2016; Cara et al., 2022; Serre et al., 2025). Thus, PFAS are of growing concern in Europe (Sonne et al., 2023), but their large-scale spatial distribution in marine environments remains poorly known, with a few relevant bioindicator species having been studied.

Monitoring contaminants in wildlife is crucial to evaluate potential risks at the species, population, and ecosystem levels, to provide key information for chemical management, and to assess the effectiveness of regulations (Treu et al., 2022). The monitoring of apex predators is a powerful tool to identify emerging pollutants and their geographical distribution in the environment, particularly for persistent, bioaccumulative, and biomagnifying chemicals (Treu et al., 2022). PFAS are currently attracting growing attention, with investigations extending to a wide range of geographical areas and species (Sun et al., 2023; Vendl et al., 2024). However, in general, PFAS are not systematically included in biomonitoring programs (Treu et al., 2022), particularly in apex predators such as raptors and seabirds. As upper predators, seabirds often accumulate significant levels of various contaminants including PFAS, which have been associated with effects on their physiology and behaviour (*e.g.*, Blévin et al., 2017; Humann-Guilleminot et al., 2024; Sebastiano et al., 2023, 2020; Sun et al., 2023; Tartu et al., 2014). Seabirds use a variety of coastal and oceanic foraging habitats with some species, such as large gulls (*Larus* sp.) also relying on terrestrial or urban areas for foraging (Gaston and Anthony, 2004; O'Hanlon et al., 2025). Seabirds show a wide range of feeding strategies, including generalist to specialist species with epipelagic, mesopelagic, or benthic diets (Gaston and Anthony, 2004). The diversity and large-scale distribution of seabirds make them particularly relevant to explore between-species and spatial variation of organic contaminants, including PFAS. Since the 2010′s, an increasing number of peer-reviewed articles on PFAS contamination in seabirds has been published (Vendl et al., 2024). Among these, PFAS concentrations in 17 seabird species across 14 European countries have been reported (*e.g.*, Sun et al., 2023). Most studies have evaluated the contamination of single species or temporal trends of PFAS concentrations in liver or in eggs (Fliedner et al., 2012; Lu et al., 2024; Pereira et al., 2021; Rüdel et al., 2011). Spatial evaluation of PFAS contamination inferred from seabird tissues is still scarce in European marine waters and limited to a few between-site comparisons (Huber et al., 2015; Löfstrand et al., 2008; Lu et al., 2024; Vicente et al., 2012). To the best of our knowledge, only Zapata et al. (2018) investigated concentrations in gull eggs from 10 Spanish Atlantic and Mediterranean sites, with a specific focus on PFOS. Among European countries, metropolitan France (France, hereafter) remains largely understudied, whereas France counts > 5,500 km of coastlines and > 55,000 km^2 of territorial waters on the English Channel and the North Sea, the Atlantic Ocean (including the Celtic Sea and the Bay of Biscay) and the Mediterranean Sea. France counts 28 breeding species of seabirds, representing > 225,000 breeding pairs (Groupement d'Intérêt Scientifique Oiseaux Marins, 2023). However, while PFAS have been investigated in French ground-, surface, and tap waters (Ministère de la transition écologique, de la biodiversité, de la forêt, de la mer et de la pêche, 2025), PFAS contamination in French marine environments remains a major knowledge gap. Overall, current data on PFAS levels in marine organisms from France are mostly restricted to fish, molluscs, and crustaceans (>30 oceanic and freshwater species) from estuaries or urban rivers (Herlory et al., 2024; Macorps et al., 2022; Miège et al., 2012; Munoz et al., 2019; Munschy et al., 2022, 2019, 2015, 2013; Serre et al., 2025). Although France offers the opportunity to study PFAS concentrations at mesoscale (Atlantic and Mediterranean) and to compare patterns of exposure (*e.g.*, by comparing species-specific contamination at different sites) of mid- to high trophic position species, PFAS have currently been examined in only four seabird species breeding in one site in the South-Western (SW) French Atlantic (Sebastiano et al., 2023, 2021) and one in the western Mediterranean (Jouanneau et al., 2025).

Here, we quantified plasma concentrations of PFAS in nine seabird species from 30 sites along the French coasts (North Sea, English Channel, Celtic Sea, Bay of Biscay, and the Mediterranean). All of these sites are located far from known PFAS production plants or industrial sites using PFAS (≥30 km, Cordner et al., 2024). Our sampling, including species using oceanic, coastal, and terrestrial foraging areas, encompassed a variety of habitats that may influence PFAS exposure. PFAS concentrations were measured in chick plasma, a low-invasive matrix thought to better reflect local exposure than adult tissues or eggs, for which the sampling is lethal (eggs) and concentrations more influenced by contaminant bioaccumulation over their life cycle (Léandri-Breton et al., 2024). The aims of this large-scale multi-species study were as follows:

- describe the plasma concentrations of 11 legacy PFAS and between-species differences in seabird chicks;
- explore potential spatial differences in PFAS contamination of seabirds between Atlantic and Mediterranean regions;
- investigate spatial differences at a finer scale, within each marine region.

The partitioning of PFAS among tissues being variable and not always well-known, with different temporal integrations depending on tissues (Gray et al., 2024; Robuck et al., 2021), comparisons with previous work have been restricted to the plasma of closely related species. Concentrations in our study are expected to be in the range of concentrations reported in the literature. We also expected higher PFAS concentrations in species or individuals feeding on marine resources compared to opportunist gull species, as previously reported (Cheng et al., 2025; Colomer-Vidal et al., 2022). PFAS sources in the Atlantic and Mediterranean regions are suspected to be different (Munschy et al., 2019, 2013), therefore individuals were expected to show different PFAS profiles depending on the marine region, with higher perfluoroalkyl carboxylic acids (PFCAs) in the Mediterranean. As shown in studies in lower trophic-level marine organisms (Munschy et al., 2019, 2013; Serre et al., 2025) and gull eggs (Knudtzon et al., 2021; Zapata et al., 2018), higher PFAS concentrations were expected in individuals sampled near large estuaries or urban sites.

2. Material and methods

2.1. Sample collection

Chicks from 9 seabird species were sampled in France, including 6 *Laridae* species (Audouin's gull *Ichthyaetus audouinii,* European herring gull *Larus argentatus argenteus*, "herring gull" hereafter, lesser black-backed gull *Larus fuscus graellsi*, great black-backed gull *Larus marinus*, yellow-legged gull *Larus michahellis*, and black-legged kittiwake *Rissa tridactyla*, "kittiwake" hereafter), the European shag *Gulosus aristotelis* ("shag" hereafter), the northern gannet *Morus bassanus* ("gannet" hereafter) and the Scopoli's shearwater *Calonectris diomedea* ("shearwater" hereafter). Chicks were sampled from 2016 to 2023, mostly in 2020 and 2021 for 28 sites, as already described in Lemesle et al. (2024a, more details in Supporting Information (SI) Section 1). In total, sampling covered 30 sites, of which 4 were in the English Channel and the North Sea, 16 in the Atlantic Ocean, and 10 in the Mediterranean coasts (Fig. 1). Sampled sites were located in urban areas, coastal lagoons, continental or remote islands, with different degrees of proximity to anthropogenic activities, but all were situated far from fluorochemical plants (>30 km, Table S1). In total, 340 chicks (n = 5 per site and species, except for few sites, see SI Section 1) were measured and blood sampled (more details about catching and sampling methods were previously published, Lemesle et al., 2024a). At the time of sampling, chicks were well-feathered, with age depending on the duration of the chick rearing (SI Section 1). Red blood cells and plasma were separated by centrifugation after sampling and were stored in a freezer at −20°C until analysis. A summary of sample sizes by species, site, and year is presented in Table S1.

2.2. PFAS analysis

PFAS were analysed in plasma at the EPOC laboratory (CNRS, Bordeaux University) following the online solid-phase extraction method described by Munoz and colleagues (Munoz et al., 2017c). Eleven PFAS including one perfluoroalkane sulfonamide (FOSA), three perfluoroalkyl sulfonic acids (PFSAs: PFHxS, PFHpS and PFOS in their linear- and branched form: L-PFHpS and Br-PFHpS, and L-PFOS and Br-PFOS, respectively), and seven PFCAs (PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA, and PFTeDA) were analysed using liquid chromatography coupled with tandem mass spectrometry (LC-ESI-MS/MS) (full names are provided in Table S2). Mass-labelled internal standards (IS) were used for quantification purposes (Munoz et al., 2017c) (Table S3), using 7-point internal calibration curves. PFAS concentrations are expressed in ng g^{-1} wet weight (ww). Quality assurance, quality control, limits of detection (LOD) and reporting (LOR) are described in SI Section 2 and Table S4.

2.3. Data mining and treatment

Molecular profiles, a heatmap, and a dendrogram generated by hierarchical clustering were used to describe and visualize PFAS contamination at the species level, the regional level or the species and sampling site levels. Molecular profiles were calculated based on the ratio of the median contributions of each PFAS to the median total PFAS sum (hereafter, "∑PFAS"). The heatmap and dendogram were both based on log_{10}-transformed PFAS concentrations and Euclidian distances (Fig. S1).

For statistical analysis, the sums of PFSA ("Σ_3 PFSAs" hereafter) and PFCA concentrations ("Σ_7 PFCAs" hereafter) were calculated for each chick by summing concentrations of each individual PFAS (Σ_3 PFSAs: PFHxS, L-PFHpS, and total PFOS – TOT-PFOS, the sum of all branched and linear isomers; and Σ_7 PFCAs: PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA, and PFTeDA).

For each aim (species level, regional level or species and sampling site levels), all calculated sums (∑PFAS, Σ_3 PFSAs, and Σ_7 PFCAs) included only PFAS reported (*e.g.*, values > LOR) in ≥ 70% of individuals. For each individual PFAS, values ≤ LOR were substituted by a

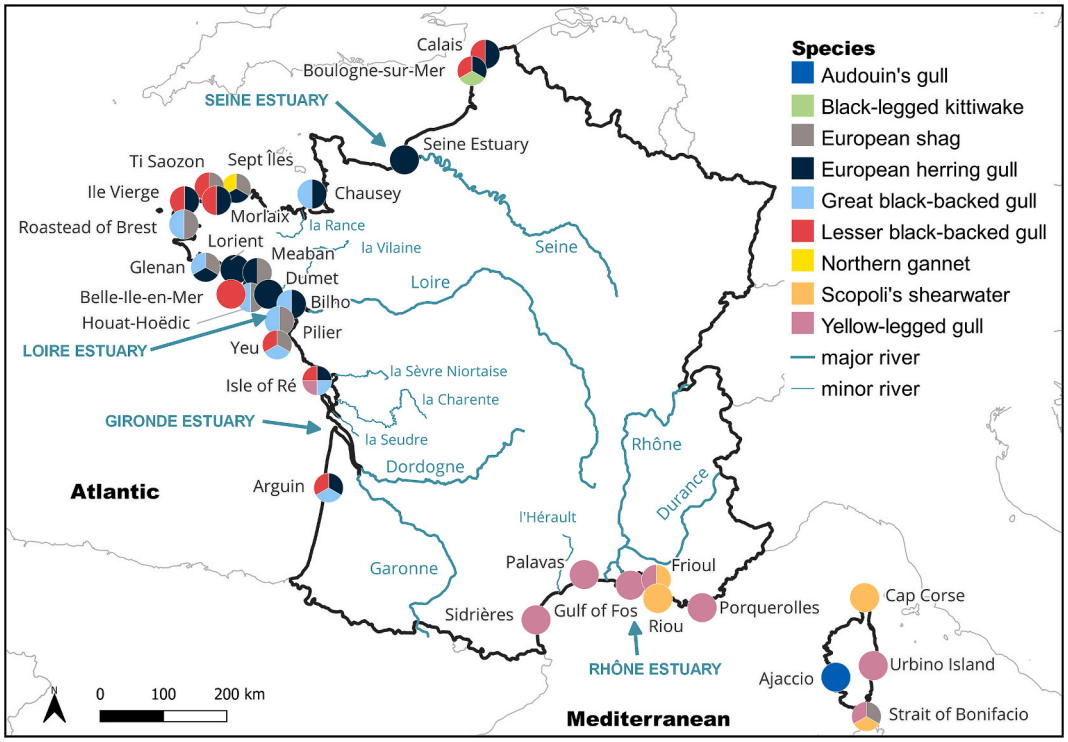


Fig. 1. Sampling map. Map of seabird chicks sampled for PFAS analysis across the Atlantic and Mediterranean French coasts. Each color refers to a species. Main French estuaries are indicated with blue arrows. Major and minor French estuaries are represented in blue. More details of sampling sizes and sites are available in Table S1.

value randomly extracted from a uniform distribution in the range [LOD; LOR] (as censored values were all > LOD and ≤ LOR). This method allows to deal with multiple LORs and is recommended when the distribution of the data is uncertain (Canales et al., 2018).

2.4. Statistical analysis

For the three aims, linear models (LMs) or generalized linear models (GLMs) were applied. GLMs were constructed with a gamma distribution and a log link function, which is relevant for continuous and right-skewed data such as PFAS concentrations (Ng and Cribbie, 2017). Model assumptions (homoscedasticity and normality of residuals) were visually assessed with the "DHARMa" package (Hartig and Lohse, 2024). We performed model selection using the Akaike information criterion for small sample sizes (AICc, "MuMin" package, Bartoń, 2023) to determine whether the model including the explanatory variable(s) performed significantly better than the null model, defined as a difference of at least two AICc units. Interannual differences of PFAS concentrations were not statistically quantified, as year was confounded with site or species, and, importantly, expected to be negligible in the short time period considered (SI Section 3 and Fig. S2).

All analyses and graphical visualizations were performed with R (version 4.2.2, "R Core Team," 2020), using the packages "ggplot2" (Wickham, 2011), "emmeans" (Lenth et al., 2023), "lme4" (Bates and Maechler, 2025), "DHARMa" (Hartig and Lohse, 2024), and "NADA2" (Julian et al., 2026). The level of statistical significance was set at $\alpha < 0.05$ for all analyses.

2.4.1. PFAS concentrations and their between-species variation

Between-species differences (irrespective of marine region and sampling site) of Σ_3 PFSAs and Σ_7 PFCAs were examined using GLMs, followed by post-hoc tests (Tukey's honest significance difference, Tukey HSD hereafter) to quantify pairwise comparisons among species. Σ_3 PFSAs and Σ_7 PFCAs were the response variables, and species was the only explanatory variable.

Between-species differences were also investigated for all individual PFAS reported in ≥ 70% of individuals from at least two species (*i.e.*, nine individual PFAS including TOT-PFOS in its two isomers, L-PFOS and Br-PFOS). For PFAS without censored data (L-PFOS and L-PFHpS), non-parametric Kruskal-Wallis tests were applied, followed by Dunn's tests. For other PFAS, the nonparametric Kaplan–Meier method and Peto–Peto–Prentice rank tests were applied to deal with left-censored data using the "NADA2" package (*cen1way* function) (Helsel, 2011; Julian et al., 2026). For all nonparametric tests, *p*-values were adjusted using the Benjamini-Hochberg method to account for false discovery rate when conducting multiple comparisons (King et al., 2023).

Between-species differences were also investigated for the proportion of the Br-PFOS isomer to TOT-PFOS ("%Br-PFOS" hereafter) using beta regression, which is appropriate for proportion data (Geissinger et al., 2022), followed by the Tukey HSD test.

2.4.2. Differences in PFAS contamination between Atlantic and Mediterranean regions

Spatial differences in Σ_3 PFSAs, Σ_7 PFCAs, and %Br-PFOS between Atlantic and Mediterranean seabirds were conducted on shags and yellow-legged gulls, the only two species sampled in both marine regions. As LM and GLM assumptions were not met, differences were examined using Kruskal-Wallis tests with sum concentrations (or percentages) as the response variables and the marine region (Atlantic or Mediterranean) as the explanatory variable.

2.4.3. Fine-scale spatial differences in seabird PFAS contamination

To assess between-site differences of PFAS concentrations, irrespective of marine region, we fitted two models (Σ_3 PFSAs or Σ_7 PFCAs as response variables) for each of six species (large gulls, shags, and shearwaters; species sampled at only one site, *i.e.*, Audouin's gulls, kittiwakes and gannets, were not included). Due to a low number of individuals, the lesser black-backed gulls sampled at Morlaix ($n = 2$) and great black-backed gulls sampled at Yeu ($n = 2$) were also excluded from the analysis. For each model (LM or GLM), site was the explanatory variable, and Tukey HSD tests were performed to quantify pairwise comparisons of PFAS concentrations among sites.

3. Results

3.1. PFAS concentrations and between-species variation

Seven PFAS were reported in ≥ 70% of individuals, including two PFSAs (PFHxS, TOT-PFOS and its two isomers: L-PFOS and Br-PFOS) and 5 PFCAs (PFNA, PFDA, PFUnDA, PFDoDA, and PFTrDA) (Tables S5 and S6), and therefore included in the analyses. Other PFAS were only reported in a few individuals (PFHpS: 53%, PFTeDA: 30%, PFOA: 14%, FOSA: 1%, Tables S5 and S6). PFSAs had the highest relative contribution to the ∑PFAS in all species. Specifically, TOT-PFOS was reported in all individuals and contributed to a minimum of 62% to a maximum of 91% of ∑PFAS in Audouin's gulls and kittiwakes, respectively (Table S7). For all species, L-PFOS had the highest concentrations among PFAS followed by Br-PFOS (Table S5). PFHxS had a high reporting frequency (99%) but a relatively low contribution to the ∑PFAS (from 2 to 5%). L-PFHpS was specifically reported in all shearwaters, gannets, and kittiwakes. Concerning PFCAs, PFNA, PFDA, PFUnDA, and PFDoDA were reported in > 96% of individuals. PFTeDA was reported in 33% of individuals, including all shearwaters, while PFOA was only reported in 14% of individuals, including all shearwaters and 80% of gannets. PFCAs contribution to the ∑PFAS ranged from 7% to 36% in kittiwakes and Audouin's gulls, respectively (Fig. 2 and Table S7). PFUnDA had the largest contribution to the ∑PFAS among PFCAs (from 2 to 13%) and the highest concentrations (Table S6). The other PFCAs had small contributions to the ∑PFAS (≤7%).

Individual PFAS, Σ_3 PFSA, and Σ_7 PFCA concentrations, as well as, %Br-PFOS varied significantly among species (ΔAICc > 152 with the null models for GLMs or $p < 0.01$ for Peto–Peto–Prentice rank tests, except PFOA, Fig. 2, Figs. S3 to S5, and Table S8). Shearwaters, kittiwakes, and gannets had the highest Σ_3 PFSA concentrations of the dataset, mostly driven by high L-PFOS concentrations, with no significant difference among these three species (Tukey HSD, $p > 0.05$). Large gulls and shags had the lowest Σ_3 PFSA concentrations, with only few significant between-species differences, mostly with small size effects (Fig. 2 and S3). Regarding PFOS isomers, kittiwakes had significantly lower %Br-PFOS (4%) compared to all the other species ($p < 0.01$), while %Br-PFOS was significantly higher in shearwaters (15%) and Audouin's gulls (13%) than in other species ($p < 0.01$, except Audouin's gulls with yellow-legged gulls and gannets). Shearwaters had also the highest concentrations of Σ_7 PFCAs and all individual PFCAs (except PFOA) when compared to all other species (Peto–Peto–Prentice rank tests, $p < 0.01$, Fig. 2, Figs. S3 and S5). Audouin's gulls had higher Σ_7 PFCAs concentrations than other Laridae species ($p < 0.05$, Fig. S3).

3.2. Differences in PFAS contamination between Atlantic and Mediterranean regions

Shags and yellow-legged gulls sampled in both the Atlantic and Mediterranean regions showed a lower PFCA contribution to the ∑PFAS in the Atlantic (21% and 19% for shags and yellow-legged gulls, respectively) than in the Mediterranean (42% and 29%, respectively) (Fig. 3 and Table S7). While Σ_3 PFSA concentrations were not significantly different in shags from the Atlantic and Mediterranean sites, Σ_7 PFCA concentrations were significantly lower in the Atlantic ($p < 0.01$; Table S9). PFUnDA was the PFCA with the highest contribution to the ∑PFAS for shags in both coasts, still with a lower relative contribution in the Atlantic than in the Mediterranean (6% and 16%, respectively). In contrast, concentrations of Σ_3 PFSAs in yellow-legged gulls were

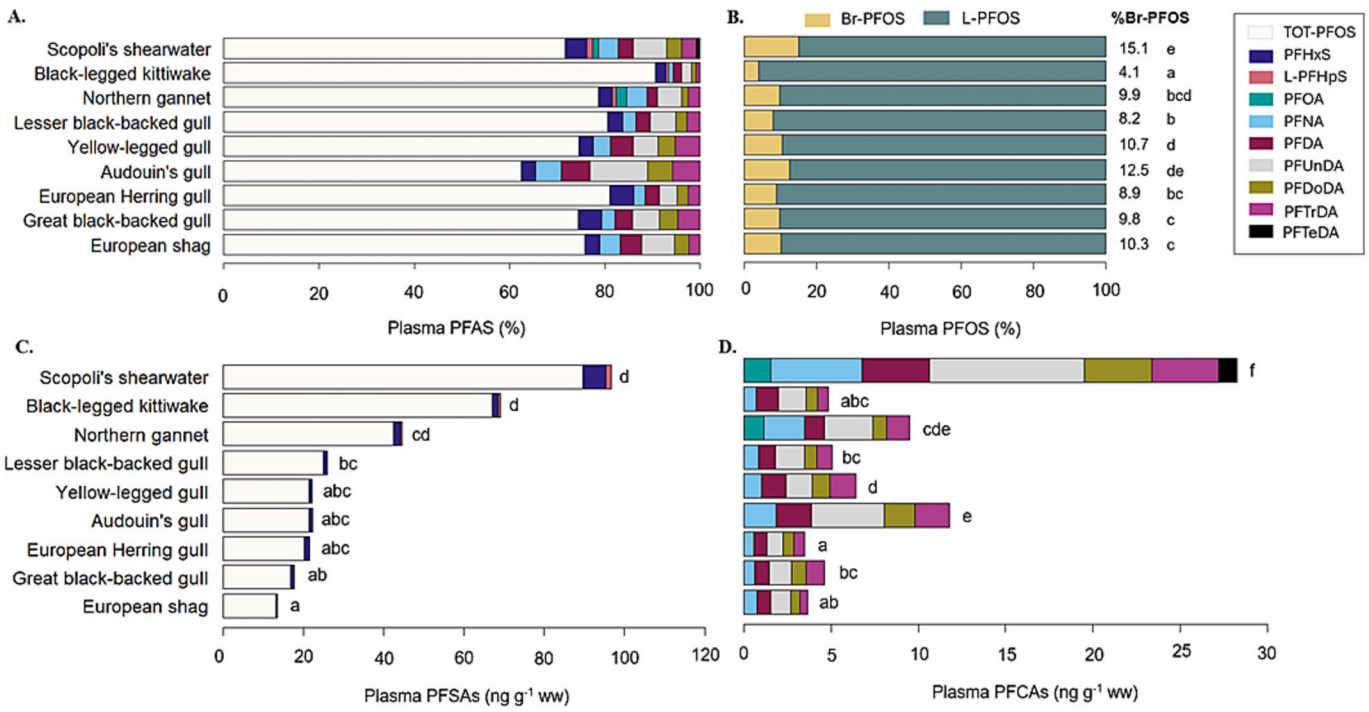


Fig. 2. PFAS concentrations, profiles, and between-species variation. A. and B. Percent stacked bar plots of PFAS and PFOS isomers (%), respectively; **C. and D.** Cumulated stacked bar plots of PFSAs and PFCAs concentrations (ng g^{-1} ww), respectively, in plasma of seabird chicks from the North Sea and the English Channel, the Atlantic, and Mediterranean French regions. For each PFAS, median values were used. In panel B, the percentages of Br-PFOS related to PFOS sum are included on the right of the cumulated stacked barplot. Species sharing the same letters do not differ statistically in their Br-PFOS percentages (B), Σ_3 PFSA concentrations (C) and Σ_7 PFCA concentrations (D), based on beta regression (B) or GLMs with Tukey HSD tests (C, D) on mean concentrations. Sampling sizes are available in Table S1.

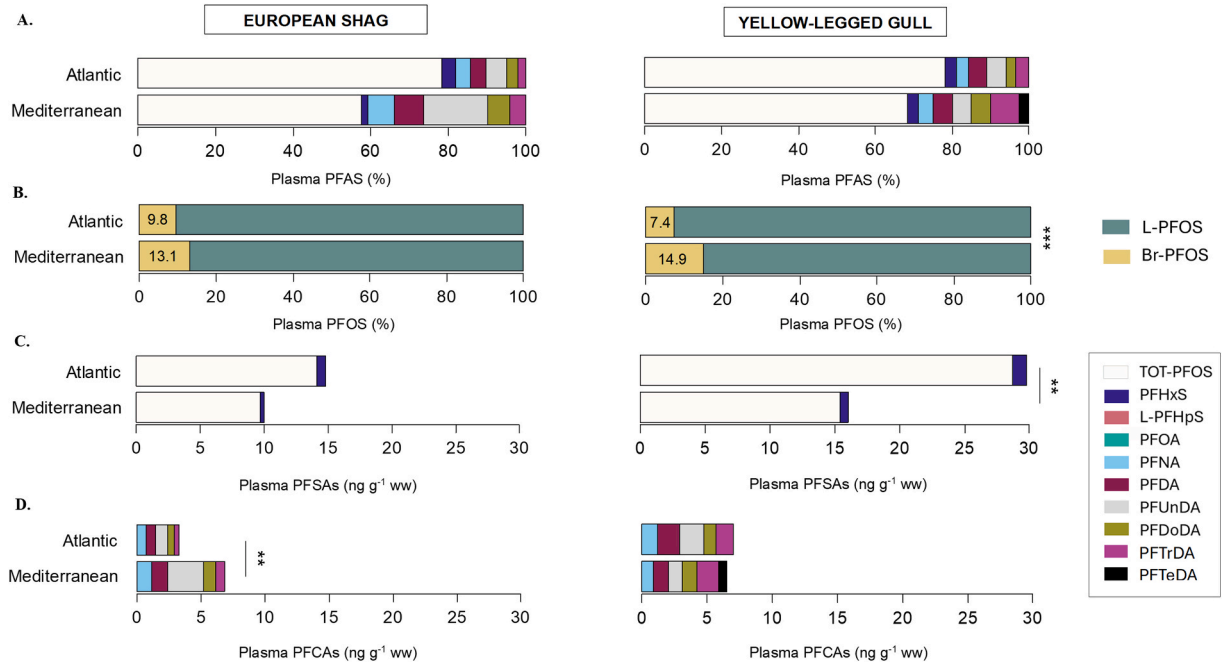


Fig. 3. Atlantic-Mediterranean comparisons. A. and B. Percent stacked bar plots of PFAS and PFOS isomers (%), respectively; **C. and D.** Cumulated stacked bar plots of PFSAs and PFCAs concentrations (ng g^{-1} ww), respectively, in plasma of European shag and yellow-legged gull chicks from the Atlantic and Mediterranean French regions. For each PFAS, median values were used. In panel B, the percentages of Br-PFOS related to PFOS sum are included on the barplot. Asterisks indicate statistical differences between the coasts ($p < 0.01$), based on mean comparisons with Kruskal-Wallis tests.

significantly higher in the Atlantic than in the Mediterranean ($p < 0.01$), while those of Σ_7 PFCAs were not significantly different between the two regions. However, PFTeDA was reported in 71% of yellow-legged gulls in the Mediterranean, while only in 35% in the Atlantic. Regarding PFOS isomers, %Br-PFOS was higher in yellow-legged gulls in the Mediterranean (15%) than in the Atlantic (7%) ($p < 0.001$), while shags had a similar but nonsignificant pattern (13% and 10% in Mediterranean and Atlantic, respectively, Table S7).

3.3. Fine-scale spatial differences in seabird PFAS contamination

Based on PFAS profiles and concentrations in seabird plasma, three main clusters were identified by hierarchical clustering (Fig. S1). A first cluster grouped individuals with the highest PFAS concentrations and diversity. This cluster included mostly Mediterranean individuals (shearwaters, Audouin's gulls, and yellow-legged gulls), but also gannets and yellow-legged gulls from the Atlantic coast. A second cluster encompassed three Atlantic sites, as well as yellow-legged gulls from Urbino Island (Mediterranean), which were the sites with the least diverse profiles or with the lowest PFAS concentrations, particularly L-PFOS (<6.2 ng g^{-1} ww). A third cluster included all other sites from the Atlantic coast and yellow-legged gulls from three Mediterranean sites (Porquerolles, Frioul, and Sidrières). In this last cluster, PFAS concentrations were intermediate between the two first clusters and L-PFHpS, PFOA, and PFTeDA were only reported in a few sites. Overall, this clustering further highlighted strong inter- and intraspecific differences within the dataset. For four sampling sites (Arguin, Boulogne-sur-Mer, Calais, and the Isle of Ré), all the species sampled were consistently grouped together, which did not occur for the other sites. Moreover,

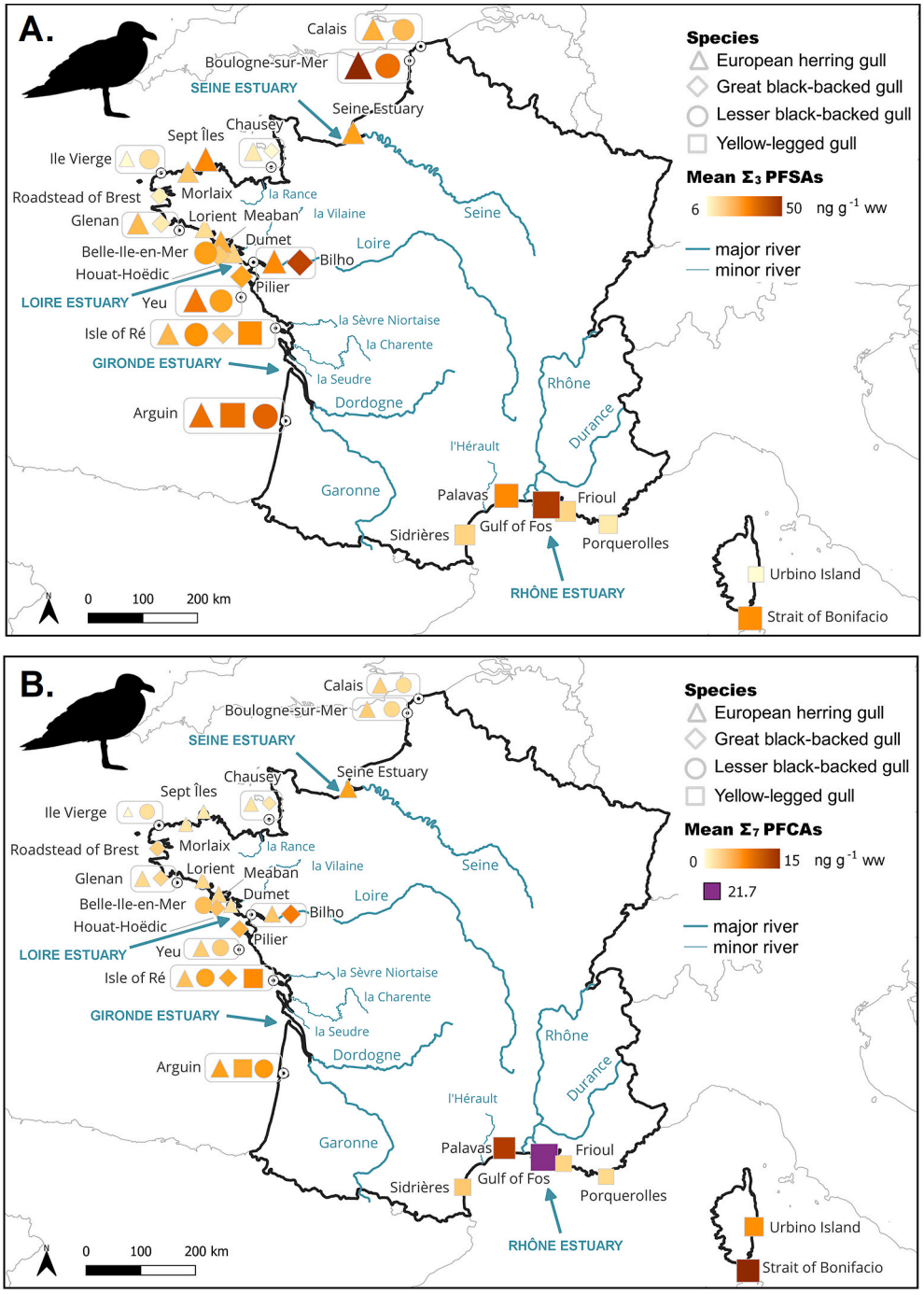


Fig. 4. Fine-scale spatial variation. Mean Σ_3 PFSA (**A.**) and Σ_7 PFCA (**B.**) concentrations (ng g^{-1} ww) in plasma of gull (*Larus* sp.) chicks across the Atlantic and Mediterranean French coasts. European herring gulls, great black-backed gulls, lesser black-backed gulls, and yellow-legged gulls are represented by triangle, diamond, circle, and square, respectively. Color and size of symbol are proportional to concentrations. Main French estuaries are indicated with blue arrows. Major and minor French estuaries are represented in blue.

with the only exception of shearwaters, the sampled sites of a same species were not grouped in the same cluster. Statistical analyses revealed that the site explained a significant part of the variation in PFAS contamination (ΔAICc $>$ 5 compared to the null models, see Figs. S6 to S9 and Table S10). For great black-backed gulls, Bilho (Loire estuary) was the site with the highest mean concentrations of Σ_3 PFSAs ($p < 0.05$) and Σ_7 PFCAs ($p < 0.05$, except Isle of Ré and Yeu) (Fig. 4, Table S11, Fig. S6 and S7). In addition, PFTeDA was reported in $\geq$ 70% of great black-backed gulls at Bilho (Fig. S7). Herring gulls from the Seine estuary had a unique profile: high PFDoDA concentrations (2.0 $\pm$ 0.9 ng g^{-1} ww) in comparison with other sites (<1.0 ng g^{-1} ww), and PFTeDA reported in all individuals (Table S12). However, mean Σ_3 PFSAs and Σ_7 PFCAs in herring gulls from the Seine estuary were similar to urban sites in northern France (Calais and Boulogne-sur-Mer) and sites close to the Loire and Gironde estuary (Yeu, Bilho, Isle of Ré, and Arguin; Fig. 4, Fig. S6 and S7). Shags from four Atlantic sites (Sept-Iles, Ti Saozon, Glenan, and Houat-Hoëdic) had overall higher Σ_3 PFSAs than shags at other Atlantic and Mediterranean sites ($p \leq 0.01$, except between Glenan and Houat-Hoëdic with two other sites, Fig. S8). Shags from these Atlantic sites and from the Strait of Bonifacio (Mediterranean) also had significantly higher Σ_7 PFCAs concentrations compared to shags at other sites ($p \leq 0.01$, except Glenan and Houat-Hoëdic with Pilier, Fig. S9). Among species sampled at both Atlantic and Mediterranean sites, yellow-legged gulls from the Gulf of Fos (Rhône estuary, Mediterranean) and the Strait of Bonifacio (Corsica Island, Mediterranean) had the highest Σ_7 PFCAs concentrations compared to all other sites ($p < 0.05$) (Fig. 4 and Fig. S9). Interestingly, PFOA was reported in 80% of yellow-legged gulls at the Strait of Bonifacio, while PFOA was rarely reported at all other sites (<20%; Table S12). Finally, shearwaters presented low between-site variation in PFAS contamination, except at Cap Corse, which had the lowest Σ_3 PFSAs and Σ_7 PFCAs concentrations compared to other sites ($p < 0.05$, Figs. S8 and S9).

4. Discussion

To the best of our knowledge this is the most comprehensive study of PFAS contamination in mid- to high trophic predators in Europe, covering two European marine regions. It reveals variations in PFAS concentrations and profiles between species and geographical areas both at the mesoscale between the Atlantic and Mediterranean, and at finer scales, with significant between-site differences even across short distances. Compared to other sites, higher PFAS concentrations were reported near three major French estuaries: the Loire and the Rhône estuaries for both Σ_3 PFSA and Σ_7 PFCA concentrations, and only Σ_7 PFCA concentrations for the Seine Estuary. PFAS concentrations were also higher at sites with low apparent anthropogenic influence, suggesting that other drivers contribute to the contamination.

4.1. PFAS concentrations and between-species variation

4.1.1. Comparison with the literature

In the present study, TOT-PFOS was the most abundant PFAS in all species, despite phased-out production in European countries since 2009 (European Commission, 2011). This is a common pattern in seabirds (Brady et al., 2024; Sun et al., 2023) and wildlife in general (Reiner and Place, 2015), related to a high persistence of PFOS in the environment (Ruyle et al., 2023), continued uses through derogations (ECHA, 2023b; United Nations Environment Programme, 2009), or/and a lag time in detecting the effectiveness of PFOS regulations (Land et al., 2018). Among all sampled species, shearwater and kittiwake chicks had the highest TOT-PFOS concentrations, which were approximately two fold lower than those measured in 1- and 4-week-old lesser black-backed chicks sampled near a fluorochemical plant in Belgium (Lopez-Antia et al., 2021). In our study, L-PFOS was the dominant PFOS isomer, while Br-PFOS accounted for a smaller proportion of TOT-PFOS (<15%), with large between-species differences. PFOS isomer profiles can provide insight into the origin of PFOS contamination (Schulz et al., 2020). Br-PFOS is a by-product of electrochemical fluorination, the historical method to produce L-PFOS (Br-PFOS accounting for 20–30% of TOT-PFOS via this method, Buck et al., 2011; Wijayahena and Aga, 2026), whereas telomerisation, which has been used more recently, only produces L-PFOS (Schulz et al., 2020). Consequently, higher contribution of L-PFOS to TOT-PFOS suggests more recent sources of contamination. However, interpretation of isomer profiles should be made cautiously, as differential bioaccumulation and elimination of linear and branched isomers may alter the original industrial signatures in biota (Wijayahena and Aga, 2026). Regarding PFOS isomers, L-PFOS has been shown to bioaccumulate to a greater extent than Br-PFOS in aquatic organisms, while Br-PFOS has faster elimination rates (Wijayahena and Aga, 2026). Kittiwakes had the lowest proportion of Br-PFOS of the dataset, and one of the highest mean L-PFOS concentrations. Kittiwakes were only sampled at Boulogne-sur-Mer, but herring gulls and lesser black-backed gulls sampled from several sites also had high L-PFOS concentrations at this same site, suggesting a local isomer profile with recent sources. Regarding PFHxS, shearwaters exhibited the highest concentrations, which were 2- to 8- fold higher than those measured in other species in our dataset, but also in previous studies on seabird chicks (Brady et al., 2024; Cheng et al., 2025). For all other species, PFHxS concentrations were similar to those found in gull chicks (Brady et al., 2024; Cheng et al., 2025) including in SW France (Sebastiano et al., 2023). Overall, in the current dataset, shearwaters, kittiwakes, and gannets had the highest Σ_3 PFSA concentrations, mostly driven by L-PFOS, but were also the only species for which L-PFHpS was reported in $\geq$ 70% of individuals. Interestingly, shearwaters, kittiwakes, and gannets are the only sampled species foraging exclusively in oceanic pelagic habitats (Table S13). Previous studies on seabirds suggested that the use of marine resources, particularly oceanic fish, can lead to higher concentrations of PFSAs (Cheng et al., 2025; Colomer-Vidal et al., 2022). This is consistent with our results in the three latter species, but not in European shags, which had overall low PFAS contamination. European shags are piscivorous and strictly marine predators, preying upon demersal and benthic fish in coastal waters (Fortin et al., 2013; Grémillet et al., 2020, see Table S13). The biomagnification potential of PFAS is thought to differ between pelagic, demersal, and benthic trophic food webs (Hedgespeth et al., 2023; Munoz et al., 2017a). In comparative studies, PFOS concentrations have been reported to be higher in pelagic organisms rather than benthic organisms (Hedgespeth et al., 2023; Munoz et al., 2017a). Our findings in shag chicks suggest a low PFOS contamination in their demersal/benthic prey, and contrast with the high contamination observed in adult shags breeding in Scotland (Carravieri et al., 2020). Gulls in our dataset had an overall low PFAS contamination. Large gulls have a varied and opportunistic diet, foraging in marine, terrestrial, and urban habitats (Duhem et al., 2005; Jouanneau et al., 2022; O'Hanlon et al., 2025), notably in association with anthropogenic sources such as landfills (*e.g.*, Duhem et al., 2005; Gyimesi et al., 2016; Nono Almeida et al., 2023). However, adults may favor landfill sites for foraging outside the breeding season or before eggs hatch, whereas it has been shown that they prefer more nutritious prey during the breeding season, thereby reducing their consumption of human waste (Lopes et al., 2021; Nono Almeida et al., 2023). In these large gulls, a higher proportion of terrestrial food relative to marine food in their diet could reduce their PFAS burden (Rozen-Rechels et al., 2026).

PFUnDA was the dominant compound among PFCAs, compared to other long-chain PFCAs, as already reported in other seabird (Alfaro Garcia et al., 2022) and raptor chicks (Dykstra et al., 2021; Gómez-Ramírez et al., 2017; Løseth et al., 2019). Shearwaters had the highest PFUnDA concentrations, which were 2- to 9- times higher than those of other species measured in our dataset. With the exception of PFOA, the shearwater was also the most contaminated species for all other PFCAs, with similar or slightly lower concentrations than those reported in previous studies in seabird chicks (Brady et al., 2024; Cheng et al.,

2025), except highly contaminated gull chicks sampled near a fluorochemical plant in Belgium (Lopez-Antia et al., 2021). Interestingly, PFOA was >LOR in all shearwaters and 80% of gannets, but with concentrations much lower than those previously reported in Belgium and China (Cheng et al., 2025; Lopez-Antia et al., 2021). Kittiwake, large gull, and shag chicks had generally low PFCA concentrations, which were lower than in adults (*e.g.*, Carravieri et al., 2020; Jouanneau et al., 2023; Sebastiano et al., 2021; Tartu et al., 2014). Overall, in our sampling, shearwaters had the highest Σ_7 PFCA concentrations, gannets and Audouin's gulls had intermediate concentrations, while other Laridae and shags had the lowest concentrations. As for PFSAs, trophic ecology has been proposed to explain higher PFCAs concentrations for species relying on oceanic resources (Colomer-Vidal et al., 2022; Gebbink et al., 2011). Surprisingly, Audouin's gulls had significant higher Σ_7 PFCAs and individual PFCA concentrations than all other large gull species, which could stem from the following non-exclusive hypotheses: 1) a strict marine diet compared to other gulls (Faggio et al., 2022) and 2) species-specific intrinsic drivers, including differences in metabolic capacities and excretion efficiency, as already suggested in yellow-legged gulls (Bertolero et al., 2015). The low PFCA concentrations in kittiwakes, despite their consumption of pelagic fish (Lemesle et al., 2024b), further suggest that diet and foraging habitat alone cannot entirely explain PFAS burdens in this dataset.

Interestingly, the shearwater, the sole representative of the Procellariformes order and of species feeding on crustaceans and squid in the dataset (Table S13), was the most contaminated species. Such high concentrations could be explained by the following non-exclusive hypotheses: 1) a specific PFAS-rich diet; 2) specific physiological mechanisms (excretion, metabolism, etc.); and 3) other extrinsic factors such as plastic ingestion, frequently reported in this species in the Mediterranean (Clark et al., 2023; Codina-García et al., 2013), but whose link to PFAS contamination remains to be clarified (Sühring et al., 2022; Szabo et al., 2020; Yu et al., 2024).

In addition to trophic ecology (foraging habitat and diet), several potential confounding factors could also have contributed to between-species variation in PFAS contamination: residual maternal contribution to chick PFAS concentrations, related to variation in maternal transfer efficiency (Ricolfi et al., 2024) and potentially influenced by wintering and pre-breeding areas (Léandri-Breton et al., 2024), as well as species-specific PFAS toxicokinetic (*e.g.*, preen oil and organ deposition, growth dilution, precursor metabolism) (Bertolero et al., 2015; Bustnes et al., 2013). Given the limited number of studies addressing these topics and the small number of species investigated, it remains difficult to explain the interspecific variation observed here. However, previous studies have shown that PFAS concentrations can change rapidly during the early growth phase (<4 weeks), although the direction of these changes is inconsistent, likely due to the combined effects of dilution of maternally transferred PFAS and increasing dietary exposure (Bustnes et al., 2013; Lopez-Antia et al., 2021; Løseth et al., 2019). Here, we sampled well-feathered chicks close to fledging, a stage at which maternal transfer likely contributes less to PFAS body burdens than dietary intake. Additional studies including PFAS quantification in prey and stable isotope analyses in seabirds to better characterise feeding ecology, as well as PFAS quantification in chick plasma at different growth stages, should be conducted to clearly identify key drivers of PFAS contamination.

4.1.2. Potential health risk of PFAS for French seabirds

In plasma, based on biological endpoints (*e.g.*, growth, survival) in adults of northern bobwhite quails (*Colinus virginianus*) and mallards (*Anas platyrhynchos*), avian toxicity reference values of PFOS were reported at 3900 ng g^{-1} ww and 240 ng g^{-1} ww in males and females, respectively (Newsted et al., 2006). All chicks in the present study are below these thresholds, but caution is needed in interpretation, as laboratory model species may not be representative of potential risks for seabird chicks (Custer, 2021). Indeed, two correlative studies on gull species from SW France have reported disruption of thyroid hormone levels at legacy PFAS concentrations that are comparable to those found in our study (Sebastiano et al., 2023, 2021). Thus, it is possible that several species of seabirds from the French seabird community might be at risk of PFAS toxic effects. In addition, the French seabird community is known to be exposed to mercury (Lemesle et al., 2024a) and likely to other organic contaminants. Therefore, further studies are recommended to experimentally investigate single- and mixture-effects, still under-considered (Dennis et al., 2022, 2021, 2020).

4.2. Differences in PFAS contamination between Atlantic and Mediterranean regions

For both shags and yellow-legged gulls, the PFAS profile and concentrations were different between the Atlantic and the Mediterranean regions. In Mediterranean individuals, PFSAs had a lower contribution to $\sum$PFAS. This pattern is related to higher Σ_7 PFCAs in shags, while yellow-legged gulls had lower Σ_3 PFSAs. In shags, Σ_3 PFSAs also tended to be lower in the Mediterranean, but with no significant difference, which could be linked to the small sample size ($n = 4$). Previous studies have reported lower PFOS concentrations in bivalves and gull eggs from the Mediterranean region compared to the Atlantic (Colomer-Vidal et al., 2022; Munschy et al., 2019, 2015, 2013). The lower concentrations of PFOS in the Mediterranean samples could indicate more historical sources than those in the Atlantic, a finding supported by the higher percentage of Br-PFOS in yellow-legged gulls sampled along the Mediterranean coast, as previously reported (Jouanneau et al., 2025). Shags had higher concentrations of $\sum_7$PFCA in the Mediterranean than in the Atlantic, whilst yellow-legged gulls from both regions showed similar concentrations of $\sum_7$PFCA. However, Mediterranean gulls exhibited a specific profile, with higher reporting frequencies and concentrations of long-chain PFCAs (PFTrDA and PFTeDA). It is interesting to note that a temporal shift in PFAS profiles, from a predominance of PFOS to a predominance of long-chain PFCAs, has been reported in sediments of the Rhône River (Mourier et al., 2019) and in crustaceans from the Rhône estuary (Munschy et al., 2019, 2015) over the past few decades. High riverine discharges of PFCAs and their precursors, together with local environmental parameters (*e.g*, salinity, temperature, and currents, Li et al., 2024; Munoz et al., 2017a; Ogunbiyi et al., 2024) could result in differences in contamination patterns in seawater and low-trophic-level marine organisms. This may explain the distinct PFAS profile in Mediterranean yellow-legged gulls, as well as the higher PFCA concentrations measured in Mediterranean shags compared with Atlantic shags. Although based on a limited sample size, the consistent results observed for the two species, which exhibit distinct trophic ecologies, suggest differential contamination between these two marine regions. According to the hierarchical clustering, Mediterranean yellow-legged gulls with high PFAS concentrations and diverse PFAS profiles were grouped together with other species sampled in the Mediterranean (Audouin's gulls and shearwaters), while yellow-legged gulls and shags from the Mediterranean with lower PFAS concentrations were grouped together with Atlantic sites. These results suggest strong heterogeneity in PFAS contamination between sites in the same marine region, which necessitate a finer-scale approach to precisely describe PFAS spatial distribution and their potential sources.

4.3. Fine-scale spatial differences in seabird PFAS contamination

Chicks and eggs of widely distributed avian species constitute relevant matrices to identify hotspots of environmental contamination, as previously shown in domestic and wild birds (Groffen et al., 2017; Jouanneau et al., 2020). In this seabird study, hierarchical clustering did not group individuals of the same species together, suggesting spatial differences in PFAS contamination. On the Atlantic coast, great black-backed gulls from the site within the Loire estuary (Bilho) presented the highest PFAS concentrations. For herring gulls, the spatial

differences were not obvious, but sites with the highest PFAS concentrations included those around estuaries (Σ_3 PFSAs: Loire and Gironde estuaries and Σ_7 PFCAs: Seine estuary). High concentrations of PFCAs were found in yellow-legged gull chicks at the site closest to the main Mediterranean estuary (Rhône estuary, Gulf of Fos site). Interestingly, PFTeDA was reported in $\geq$ 70% of gull chicks in only six Atlantic and Mediterranean sites, including those close to the three main French estuaries (Seine, Loire, and Rhône estuaries). National monitoring of shellfish along the French coasts has previously shown that the highest PFAS concentrations occurred in the vicinity of these three major French estuaries (*e.g.*, Herlory et al., 2024; Munschy et al., 2019; Serre et al., 2025). Widespread occurrence of PFAS have been previously reported in water and biota from the Seine, Loire, and Rhône rivers (Couderc et al., 2015; Labadie et al., 2021; Macorps et al., 2022; Munoz et al., 2015; Schmidt et al., 2019; Ministère de la transition écologique, de la biodiversité, 2025). These three rivers flowed through highly urbanized regions with dense populations and industrial activities involving PFAS (Cordner et al., 2024; Teymoorian et al., 2025). However, high spatial heterogeneity was detected between sites close to each other, including in the surroundings of estuaries (*e.g.*, Gulf of Fos and Frioul in the Mediterranean, and Bilho and Pilier in the Atlantic). Diet preferences of seabirds around estuaries could explain these findings and must therefore be precisely known to use seabirds as indicators of estuarine contamination.

Large gull species from Boulogne-sur-Mer, Arguin, and Isle of Ré also had high concentrations of different PFAS depending on site (Σ_3 PFSAs: Boulogne-sur-Mer, Σ_7 PFCAs: Isle of Ré, Σ_3 PFSAs and Σ_7 PFCAs: Arguin). Interestingly, these three sites are located near densely populated areas (>100 inhabitants/km^2; Table S1) (Agence nationale de la cohésion des territoires, 2021). Specifically, Boulogne-sur-Mer is an urban city in the English Channel with a strong industrial and metallurgical history (Francescangeli et al., 2016; Lottin, 2014), Isle of Ré is a continental island close to three river mouths, while Arguin is a sandbank located at the entrance of a coastal lagoon connected to the Atlantic Ocean (Arcachon Basin). Previous studies on freshwater, soil, fish, seabird plasma, and eggs have reported that proximity to urban and industrialized areas could lead to higher PFAS concentrations (*e.g.*, Knudtzon et al., 2021; Labadie and Chevreuil, 2011; Macorps et al., 2022; Munoz et al., 2018; Wells et al., 2024). The three sites are also located in intensive agricultural regions (Nowak and Marliac, 2024), an activity reported to be a significant source of PFAS due to their use as active pesticide ingredients (Donley et al., 2024; Joerss et al., 2024; Ogawa et al., 2020). These local contexts could explain high PFAS concentrations, but shellfish sampled close to Arguin and Isle of Ré had PFAS concentrations consistent with other French sites (Munschy et al., 2019, 2013), calling for further investigations at the food web level. Moreover, herring gulls, yellow-legged gulls, and shags from four Atlantic islands (Sept-Iles, Ti Saozon, Glenan, and Houat-Hoëdic) and one Mediterranean archipelago (Strait of Bonifacio) with low human population densities and far from the main estuaries (~130 to 800 km) also had high PFAS concentrations. Interestingly, PFOA was almost exclusively detected at these five sites. The high PFAS concentrations observed at these sites were unexpected, suggesting that factors other than proximity to major estuaries or areas of high anthropogenic influence (industrial activities and human population densities) may contribute to PFAS contamination. Multiple oceanographic, biophysical, and biogeochemical processes are probably involved in determining the spatial distribution of PFAS (Li et al., 2024; Munoz et al., 2017b; Ogunbiyi et al., 2024). As previously discussed, extrinsic drivers could also lead to differences within the same species at different sites. For example, site-specific differences in seabird diet, driven by local availability and urban habitats (*e.g.*, local prey stock, landfills, and fishery discards), could also explain spatial variation in PFAS contamination. In contrast to other species, shearwaters showed low between-site variation in PFAS concentrations. As shearwaters are strictly related to marine resources and forage in oceanic waters, their contamination might be weakly influenced by breeding site location. The modest sample size per site in our study was intended to provide an initial assessment of contamination along the French coastline rather than to identify the main factors driving the spatial heterogeneity in PFAS concentrations. Further investigations on the trophic ecology of the targeted species at the different sites are needed to confirm the role of diet and foraging habitats in PFAS contamination.

5. Conclusions

Our study is the first European large-scale survey of PFAS in seabirds and detected significant differences in PFAS contamination between species, the Atlantic and the Mediterranean regions, and even among nearby sites, along the French coastlines. This multi-species and multi-site study revealed spatial heterogeneity in legacy PFAS concentrations and shed light on potential risks of PFAS exposure in French seabirds, calling for management of legacy PFAS at the most contaminated sites, and urgent assessment of emerging PFAS. Some PFAS have been widely reported here despite being phased-out, which illustrates the need for long-term monitoring using wildlife bioindicators to evaluate the effectiveness of regulations.

CRediT authorship contribution statement

Prescillia Lemesle: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Alice Carravieri:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis. **Gauthier Poiriez:** Project administration, Investigation. **Romain Batard:** Investigation. **Aurélie Blanck:** Writing – review & editing, Resources, Investigation. **Coraline Bichet:** Writing – review & editing, Investigation. **Gilles Faggio:** Writing – review & editing, Investigation. **Jérôme Fort:** Writing – review & editing, Resources, Funding acquisition. **Fabrice Gallien:** Investigation. **William Jouanneau:** Writing – review & editing, Investigation. **Pamela Lagrange:** Writing – review & editing, Investigation. **Carole Leray:** Investigation. **Ignacio Martinez-Alvarez:** Investigation. **Aourell Mauffret:** Writing – review & editing, Methodology, Investigation. **Karen D. McCoy:** Writing – review & editing, Resources, Investigation, Funding acquisition. **Patrick Pardon:** Methodology. **Pascal Provost:** Investigation. **Bernard Recorbet:** Investigation. **Manrico Sebastiano:** Writing – review & editing, Investigation. **Nathalie Wessel:** Investigation, Conceptualization. **Pierre Labadie:** Writing – review & editing, Resources, Methodology, Investigation. **Hélène Budzinski:** Writing – review & editing, Resources, Methodology, Investigation. **Olivier Chastel:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Paco Bustamante:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Acknowledgments

This work has been approved by the French Animal Ethics Committee (authorization number: APAFIS #15629–2019032823161213; APAFIS#26125-2020022111202684), certificates of approval is available upon request. Authorisations to work in the Gulf of Fos were provided by Grand Port Maritime de Marseille and DDTM 13/Service Mer Eau Environnement/Pôle Nature et Territoires (n◦13-2018-02-22-003) and the town of Port-Saint-Louis-du-Rhone. This work was funded by the OFB (Office Français de la Biodiversité) and the ANR (Agence Nationale

de la Recherche) through the Suivi des contaminants et de leurs effets chez les oiseaux marins project (OFB.20.0409), the ToxSeaBird project (ANR-21-CE34-0019), the ECODIS project (ANR-20-CE34-0002) and the EXPO and MULTISTRESS projects (Région Nouvelle Aquitaine). This work was supported by the Partnership for the Assessment of Risks from Chemicals (WP4) funded by the European Union through the Grant 101057014. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the EU or the European Research Executive Agency; neither the EU nor the granting authority can be held responsible for them. Some of the samples used for this work were collected within the framework of the Camargue Health-Environment "Zone Atelier" (ZACAM) of the "LONG- TERM SOCIO-ECOLOGICAL RESEARCH – LTSER" network (RZA), funded by the French National Center for Scientific Research (CNRS-EE). PL was funded by the Agence Nationale de la Recherche through the project ToxSeaBird (ANR-21-CE34-0019), AC by the Région Nouvelle Aquitaine through the Excellence Chair ECOMM, and MS was funded by the Région Nouvelle Aquitaine (Projet MULTISTRESS). The PLATINE platform (Organic Environmental Analytical Chemistry Platform) at UMR 5805 EPOC provided the analytical facilities dedicated to this project. We are particularly grateful to the following institutions and their staff for their invaluable help, support and technical assistance during fieldwork: the Groupe ornithologique et naturaliste (GON agrément régional Hauts-de-France, Cédric Beaudoin, Marie-Noëlle Camberlein, Pierre Camberlein, Sylvain Dromzee, Nathan Legroux, Eric Petit-Berghem, Sylvain Poisblaud, Jean-Michel Sauvage, Denis Tirmarche), the Parc Naturel Marin des estuaires picards et de la mer d'Opale (Carole Perron and Camille Gilliers), the Maison de l'Estuaire (Martin Blanpain, Damien Ono-dit-Biot, Faustine Simon), the Groupe Ornithologique Normand (GONm), the Ligue pour la Protection des Oiseaux (LPO, the LPO station Ile-Grande: Grégoire Delavaud; the Réserve Naturelle nationale de Lilleau des Niges: Julien Gernigon, Jean Christophe Lemesle, Frédéric Robin; the LPO station Vendée: Marion Rabourdin), the Réserve Naturelle Nationale des Sept-Iles (Pascal Provost, Armel Deniau), Bretagne Vivante (Marion Diard, David Hémery, Marine Leicher, Yann Jacob, Bastien Jorigné, Joris Laborie, Margot Le Guen, Bruno Querné), the Parc Naturel Marin d'Iroise (Céline Gicquel, Myriam Guéguen, Hélène Mahéo, Yannis Turpin), the Parc Naturel Régional d'Armorique (Anne Corbé, Agathe Larzillière), the Parc Naturel Régional du Morbihan (David Lédan), the Société pour l'Etude et l'Aménagement de la Nature dans le Sud-Ouest (SEPANSO, Matthias Grandpierre, Christophe Le Noc), the municipality of Leucate city (Julien Robert), the Parc Naturel Régional de la Narbonnaise en Méditerranée (Kattalin Fortuné-Sans, Guilhem Mollera), the Conservatoire d'espaces naturels d'Occitanie (Héloïse Durand, Rémi Jullian), the Tour du Valat (Thomas Blanchon, Marion Vittecoq), the MiVEGEC laboratory (Florence Nono-Almeida), the Parc National des Calanques (Lorraine Anselme, Jean-Patrick Durand, Alain Mante, Célia Pastorelli, Aurélien Robin), the Centre d'Ecologie Fonctionnelle et Evolutive (CEFE, Thierry Boulinier, Juliet Lamb), the Réserve Naturelle des Bouches de Bonifacio, the Office de l'Environnement de la Corse (Jean-Michel Culioli, Jean-Baptiste Lanfranchi, Sébastien Susini), and the Conservatoire du Littoral (Cyril Cros, Virginie Paolacci, Matthieu Zanca-Rossi). We also thank Sophie Lorioux and Fanny Cusset (LIENSs) for their help during fieldwork. We express our thanks to David Pinaud and Clayre Grumiaux for their help and feedback on statistics and QGIS. We are grateful to the three anonymous reviewers who provided valuable comments on the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2026.110386.

Data availability

Data will be made available on request.

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