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1 **Physiological effects of PFAS exposure in seabird chicks: a multi-species**  
2 **study of thyroid hormone triiodothyronine, body condition and**  
3 **telomere length in South Western France**

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20 **Abstract**

21 There is growing evidence that poly and perfluoroalkyl substances (PFAS) exposure leads to the disruption  
22 of thyroid hormones including thyroxine (T4) and triiodothyronine (T3), and may affect telomeres,  
23 repetitive nucleotide sequences which protects chromosome ends. Many seabird species are long-lived top  
24 predators thus exhibit high contaminant levels, and PFAS-disrupting effects on physiology have been  
25 documented especially in relation to the endocrine system in adults. On the contrary, studies on the  
26 developmental period (i.e., chicks), during which exposure to environmental contaminants may have a  
27 greater impact on physiological traits, remain scarce to this date. We carried out a multi-species study with  
28 the aim to assess whether and to which extent chicks of four gull species (herring gull, great and lesser  
29 black-backed gull, yellow-legged gull) in South Western France are contaminated by PFAS, and to bring  
30 further evidence about their potential physiological consequences. Linear PFOS showed concentrations of  
31 concern as it was generally more than 10 times higher than the other PFAS, and exceeded a threshold  
32 toxicity level (calculated from previous studies in birds) in almost all sampled chicks. Nonetheless, in herring  
33 gull male chicks, total T3 levels were significantly and negatively associated with perfluorodecanoate  
34 (PFDA) and perfluorododecanoate (PFDoDA) and positively associated with perfluorotetradecanoate  
35 (PFTeDA) in female chicks. Total T3 levels were also positively associated with PFDoDA in great black  
36 backed gull male chicks and with perfluorotridecanoate (PFTTrDA) in lesser black backed gull chicks. In lesser  
37 and great black-backed gulls, both females and males showed significant negative associations between  
38 several PFAS and their body condition, and a positive association between telomere length and L-PFOS in  
39 the yellow-legged gull. These results corroborate previous findings and need to be further explored as they  
40 suggest that PFAS may interfere with the physiological status of chicks during the developmental period,  
41 potentially inducing long-lasting consequences.

42

43 Keywords: seabirds, contaminants, PFAS, telomeres, thyroid hormones, physiology

44 **Introduction**

45 Poly and perfluoroalkyl substances (PFAS) are a group of synthetic compounds that have been widely used  
46 over the past decades, especially considering their thermal and chemical stability, which enables them to  
47 be used in nonstick cookware, waterproof and stain resistant fabrics, and firefighting foam amongst many  
48 other commercial products (Wang et al., 2017). Although they were initially thought to be harmless  
49 substances, PFAS currently represent a major global health concern. Because of their high persistence in  
50 the environment (Cousins et al., 2022), their ubiquitous presence (Giesy and Kannan, 2001), and their  
51 bioaccumulation potential (at least for some PFAS; Conder et al., 2008), there is growing evidence  
52 regarding the toxicity of these compounds for both humans and animals (Sebastiano et al., 2020; Sinclair et  
53 al., 2020; Wang et al., 2017). PFAS are known to have a strong affinity for serum carrier proteins including  
54 albumin, transthyretin and thyroid binding globulin, thereby having endocrine-disrupting capabilities (Kar  
55 et al. 2017; Lihui et al. 2023). They can affect immunocompetence, disrupt the endocrine system, and  
56 impact on several physiological pathways in both humans and laboratory animals (DeWitt, 2015;  
57 Sunderland et al., 2019).

58 PFAS have been found globally in wildlife (Giesy and Kannan, 2001). It is increasingly recognized  
59 that the release of these chemicals into the environment is a major threat for wildlife and population  
60 viability, yet the consequences of PFAS exposure in wildlife remain poorly investigated. Determining how  
61 PFAS affect free-living vertebrates is challenging, but such compounds have been linked to a wide range of  
62 biological effects. One of the well-studied example of PFAS disrupting capacities lies with the competition  
63 of PFAS with thyroxine (T4) for binding to the thyroid hormone transport protein transthyretin (TTR). These  
64 disruptions may reduce circulating thyroid hormone levels including triiodothyronine (T3) and thyroxine  
65 (T4) (Kar et al., 2017; Ren et al., 2016). Indeed, the literature supports such thyroid-disrupting effect of the  
66 exposure to both old- and new-generation PFAS (Coperchini et al., 2020), but studies on these disrupting  
67 effects are underrepresented in wildlife.

68 The disruption of thyroid hormone levels in birds may be highly detrimental as they play a major  
69 role for development, behaviour, metabolism and reproduction (McNabb, 2007). In thick-billed murre *Uria*  
70 *lomvia*, the levels of free T3 (FT3) increased with increasing concentrations of certain PFAS, while total T3

71 (TT3) decreased with increasing PFAS levels, suggesting thyroid disruption (Choy et al., 2022). Recent work  
72 on the glaucous gull *Larus hyperboreus* found a positive association between perfluorooctanesulfonate  
73 (PFOS) and FT3 levels (Mernes et al., 2017). Similarly, adult great black backed gulls *Larus marinus* exposed  
74 to high PFAS levels showed a positive association between TT3 and several PFAS in females, but an  
75 opposite pattern was found in males (Sebastiano et al., 2021). PFAS were also positively associated with  
76 circulating thyroid hormones and thyroid gland activity in peregrine falcons *Falco peregrinus* chicks (Sun et  
77 al., 2021). These findings suggest a strong impact of PFAS exposure on the thyroid functioning and thyroid  
78 hormone regulation in birds. However, given the mixed results and the importance of optimal thyroid  
79 hormone levels in birds, this relationship needs to be more extensively investigated.

80         Telomere length and telomere dynamics (i.e. their variation in length over time) also represent  
81 potential physiological markers to investigate the toxicological consequences of PFAS on wildlife health.  
82 Telomeres are regions of repetitive DNA sequences which protect the ends of chromosomes and play a key  
83 role in aging and cell senescence (Aubert and Lansdorp, 2008). Their length represents a relevant measure  
84 of physiological stress in vertebrates (Angelier et al., 2018; Chatelain et al. 2020). In birds, telomeres are  
85 related to maximum lifespan (Tricola et al., 2018), reflect developmental stress (Boonekamp et al., 2014),  
86 and are an index of individual quality (Angelier et al., 2019), thus representing a key physiological marker to  
87 investigate the impact of contaminants on fitness (Louzon et al. 2019). Previous work in birds found that  
88 certain PFAS are positively associated with telomere length and telomere dynamics (Blévin et al., 2017a;  
89 Sebastiano et al., 2020). For instance, a positive relationship between PFASs and telomere dynamics was  
90 documented in black-legged kittiwakes *Rissa tridactyla*, with elongated telomere in birds bearing the  
91 highest PFAS concentrations (Blévin et al., 2017a). Similarly, glaucous gulls exposed to higher  
92 concentrations of certain PFAS showed the slowest rate of telomere shortening, and, in some individuals,  
93 telomere elongation (Sebastiano et al., 2020). However, no relationship was found between PFAS and  
94 telomere length in white-tailed eagle *Haliaeetus albicilla* chicks (Sletten et al., 2016). The physiological  
95 mechanisms through which PFAS disrupt key physiological processes and organism functioning need to  
96 represent a priority of ecotoxicological studies as this remains a largely unexplored area of research in  
97 wildlife.

98           Because many seabird species are long-lived top predators, they often exhibit high levels of  
99 persistent and biomagnifying contaminants (Rowe, 2008), and are considered as ideal models to assess the  
100 occurrence, levels and fate of contaminants in the environment. Seabird also aggregate in colonies during  
101 the reproductive season, offering the opportunity to investigate several species simultaneously and from  
102 the same geographic area, which can help us understand the factors driving intra- and inter-specific  
103 variation in contaminant exposure. So far, most of our knowledge about toxicological responses to  
104 contaminant exposure in seabirds relies upon studies conducted on adult birds. Comparatively much less is  
105 known on chicks as compared to adults, although detrimental consequences early in life are key  
106 determinant of the future fitness outcomes. Here, we carried out a multi-species study with the aim to  
107 assess to which extent seabird chicks of four seabird species from South Western France (European herring  
108 gulls *Larus argentatus*, lesser black-backed gulls *L. fuscus*, great black-backed gulls, and yellow-legged gulls  
109 *L. michahellis* are contaminated by PFAS. Previous work on the adults of the same species reported the  
110 presence of high concentrations of PFAS (e.g., range between 26.51 and 119.69 ng/g PFOS in lesser black-  
111 backed gulls; Sebastiano et al., 2021), with certain PFAS showing comparable or higher concentrations than  
112 seabird colonies known to be highly contaminated (Sebastiano et al., 2021). The combination of high levels  
113 of environmental contaminants and the simultaneous presence of several species in the same geographical  
114 location makes the study area ideal to explore the animals' response to environmental contamination in  
115 the wild. We therefore additionally investigated the relationship between exposure to PFAS and  
116 physiological endpoints including the levels of the plasma thyroid hormone T3 – i.e. the active form of  
117 thyroid hormones and telomere length in growing chicks. We expected to find similar association than  
118 those found in adults (mostly positive associations between TT3 and PFAS; Sebastiano et al. 2021), but the  
119 strength of these associations could be either reduced (due to the expected lower concentrations in chicks)  
120 or exacerbated (due to the increased sensitivity in chicks).

121

## 122 **Materials and Methods**

123 Sampling

124 Field work has been carried out from 2016 to 2019 at the Lilleau des Niges Natural Reserve (46° 13' 53" N, -  
125 1° 30' 22" W), managed by the Ligue pour la Protection des Oiseaux (LPO) located on the North side of Ile  
126 de Ré, France, as a part of a monitoring program for PFAS in the region. From 2016 to 2018, 21 European  
127 herring gulls *Larus argentatus* (n=10 in 2016, n=11 in 2018); 20 lesser black-backed gulls *L. fuscus* (n=10 in  
128 2016, and n=10 in 2018); and 17 great black-backed gulls *L. marinus* (n=9 in 2016, and n=8 in 2018) chicks,  
129 were captured and sampled. In 2019, 12 yellow-legged gulls *L. michahellis* were additionally sampled, for a  
130 total of 70 chicks.

131 Chicks were captured by hand on their nests, when they were all the same age (approximately 1  
132 month old). After capture, 2mL of blood was collected from the alar vein using a heparinized syringe and a  
133 25-gauge needle. Blood was kept in a cold container in the field and centrifuged for 10 min at 8,000 x g at  
134 20 °C at the laboratory within a few hours after collection to separate plasma and red blood cells, which  
135 were kept frozen at -20 °C until laboratory analyses. Skull and tarsus length were measured with an  
136 accuracy of 0.1 mm using a caliper. Wing length was also measured with an accuracy of 1 mm using a ruler,  
137 and birds were weighted to the nearest 5 g using a Pesola spring balance.

138 DNA was extracted from erythrocytes and the sex of the birds was determined at the CEBC ('Service  
139 d'Analyses Biologique') by polymerase chain reaction (PCR) amplification of two highly conserved genes  
140 (CHD) as described in (Fridolfsson and Ellegren, 1999). Amplification was performed in 20µl final volume  
141 with an Eppendorf Mastercycler using 0.5 U Taq DNA polymerase, 200µM dNTPs, 10mM Tris-HCl pH 8.3,  
142 50mM KCl, 1.5mM MgCl<sub>2</sub> and 0.4µM of primers 2550F (5'- GTTACTGATTCGTCTACGAGA-3') and 2718R (5'-  
143 ATTGAAATGATCCAGTGCTTG-3').

144 Blood volume was too low to conduct laboratory analysis in one lesser black-backed gull chick.  
145 Therefore, a total of 69 chicks were included in the final dataset (21 European herring gull (n=10 in 2016,  
146 n=11 in 2018); 19 lesser black-backed gull (n=9 in 2016, and n=10 in 2018); 17 great black-backed gull (n=9  
147 in 2016, and n=8 in 2018); and 12 yellow-legged gull chicks from 2019.

148 PFAS analyses

149 A total of 14 PFAS were analysed at the EPOC lab in each plasma sample using liquid chromatography  
150 coupled with tandem mass spectrometry (LC-ESI-MS/MS) on a 1290 LC system interfaced with a 6490 triple

151 quadrupole mass spectrometer operated in Multiple Reaction Monitoring mode (MRM; Agilent  
152 Technologies, Massy, France), including eight perfluoroalkyl carboxylic acids: branched- (Br-PFOA) and  
153 linear-perfluorooctanoate (L-PFOA), perfluorononanoate (PFNA), perfluorodecanoate (PFDA),  
154 perfluoroundecanoate (PFUnDA), perfluorododecanoate (PFDoDA), perfluorotridecanoate (PFTTrDA),  
155 perfluorotetradecanoate (PFTeDA); and six perfluoroalkyl sulfonic acids: perfluorohexanesulfonate (PFHxS),  
156 branched- (Br-PFHpS) and linear-perfluoroheptasulfonate (L-PFHpS), branched perfluorooctanesulfonate (Br-  
157 PFOS), linear perfluorooctanesulfonate (L-PFOS), and perfluorooctanesulfonamide (FOSA). Analytical  
158 standards of native PFAS along with a series of 10 <sup>13</sup>C, <sup>18</sup>O or D mass-labelled internal standards used for  
159 quantification purposes were supplied by Wellington laboratories. All reagents were analytical grade or  
160 equivalent and further information on recoveries can be found in Munoz et al. (2017). Analyte  
161 quantification was performed using six-point internal calibration (0.1-100 ng/g plasma equivalent).  
162 Accuracy was determined based on replicate analyses of chicken plasma samples spiked at 2 ng/g (n=15). A  
163 detailed protocol for the methodology used for analyzing the PFAS, quality assurance/ quality control  
164 (QA/QC) results, detection frequencies, accuracy, and LOD of all PFAS analyzed in the study can be found in  
165 the supporting information and in Table S1 and Table S2. Br-PFOA, L-PFOA, Br-PFHpS, and FOSA had a  
166 detection frequency below 40% of samples and were not included in the statistical analyses.

#### 167 Thyroid hormone analyses

168 Total T3 was determined by radioimmunoassay at the CEBC ('Service d'Analyses Biologique') in all samples  
169 collected until the breeding season of 2018, after which laboratory analyses were performed (therefore in  
170 21 European herring gulls; 19 lesser black-backed gulls; 17 great black-backed gulls, but not in yellow  
171 legged gull samples collected later on in 2019). Briefly, 25 µL of plasma was incubated for 24h at 4 °C with a  
172 known concentration (10000 cpm) of T3 marked with the radioisotope Iodine-125 (T3-125I, Perkin Elmer,  
173 US, reference: NEX110X100UC) and an antibody Ab (polyclonal rabbit antiserum, Sigma-Aldrich, US,  
174 reference: T-2777). Because Ab is available in a limited concentration, T3 and T3-125I compete for Ab, to  
175 which they bind. Therefore, after incubation, there is a bound fraction (T3 and T3-125I bound to Ab) and a  
176 free fraction (T3 and T3-125I unbound to Ab), which are separated by adding a sheep anti-rabbit antibody  
177 (whole anti-serum anti rabbit IgG produced in sheep), incubated for 12h at 4 °C followed by centrifugation



178 at 4,300 x g at 18-20°C for 45 min. The bound fraction is then counted with a wizard 2 gamma counter  
179 (Perkin Elmer, US). Pooled plasma of diverse gull samples was serially diluted and produced a dose-  
180 response curve parallel to the T3 standard curve.

181 All samples had TT3 concentration above the minimum detectable concentration of 0.07 ng/ml  
182 (LOD). All samples were run in duplicates. Samples that had a coefficient of variation above 12% between  
183 the two duplicates were done in triplicates. The intra-assay coefficient of variation was 9.7%, while the  
184 inter-assay coefficient of variation amounted to 15.1%.

#### 185 Telomere analyses

186 Telomere length analyses were performed at the CEBC ('Service d'Analyses Biologique') in red blood cell  
187 samples collected from 2016 to 2019, using a real-time quantitative polymerase chain reaction (qPCR)  
188 technique as previously done (Sebastiano et al., 2020). Briefly, DNA was extracted from red blood cells  
189 using DNeasy Blood and Tissue Kit (Qiagen), checked for quality and quantity with an optical density  
190 spectrophotometer (Nanodrop ND-1000, Thermo Fisher Scientific, US) and by running DNA samples on a  
191 gel. RAG1 (Recombination activating gene 1) gene was selected as our reference gene ("single copy gene").  
192 The qPCR was performed with the telomere primers (Tel1b and Tel2b) and RAG1 primers (RAG1\_F and  
193 RAG1\_R), using 2.5 ng of DNA per reaction. Telomere length is expressed relative to the single copy  
194 reference gene (RAG1) measured on the same DNA sample (i.e., T/S ratio). Further clarifications on the  
195 methodology used for telomere length estimation can be found in the Supporting information. One sample  
196 could not be done in lesser black-backed gull chicks. A total of 67 samples - for which we had both telomere  
197 length and PFAS (21 European herring gulls; 18 lesser black-backed gulls; 17 great black-backed gulls; 11  
198 yellow-legged gull chicks from 2019) - were therefore available for further analyses.

#### 199 Statistical analyses

200 First, we investigated whether PFAS concentrations showed significant differences between males and  
201 females, or between the sampling year (2016 and 2018). We further tested whether any difference in  
202 absolute PFAS concentrations occurred among the studied species (herring gulls, lesser and great black-  
203 backed gulls) using linear models. Each PFAS was considered as a dependent variable while the factors  
204 *Species*, *Year*, *Sex*, and their interactions (e.g. *Species:Sex*) were considered as predictors.

205           Second, we explored the association between i) TT3, ii) telomere length, and iii) the body condition  
206 (as dependent variables), and PFAS (as predictor) in samples collected in 2016 and 2018 using linear  
207 models. The body condition (hereafter body mass index *BMI*) has been calculated using the body mass  
208 adjusted by a coefficient generated by the relationship between the body mass and a linear body  
209 measurement (i.e. skull length) using the formula  $[\text{body mass} * \text{mean skull length} / \text{skull length}]^{\text{overall}}$   
210 coefficient of the linear model between body mass and skull], as described in Peig and Green (2009). The  
211 skull length has been used because it is a very reliable and repeatable skeletal measurement and is highly  
212 correlated with body mass in all species (Pearson's correlation coefficient above 0.75 in each species). A  
213 three-way interaction term between PFAS and the factors *Species* and *Sex*, was used to investigate whether  
214 the association between the dependent variables (i.e., TT3, telomere length, and BMI, respectively) and  
215 PFAS could be related to the gender or was only occurring in a particular species. These models additionally  
216 included the *Year* of sampling (as a factor, to control for the temporal variation in total T3 and PFAS  
217 between 2016 and 2018), and the *Skull length* (as a covariate), to control for any age-related difference  
218 among chicks. The models on TT3 and telomere length also included the *BMI* (as a covariate, to control for  
219 the individual condition of birds). In these models, total T3 and PFAS were  $\log_{10}$  transformed.

220           Because data on yellow-legged gulls were only collected in 2019, linear models for this species were  
221 done separately to test the association between telomere length and *BMI* (as dependent variables) and  
222 PFAS (as predictors). In all models on yellow-legged gulls, the factors *Sex*, *BMI* and the interaction between  
223 PFAS and *Sex* were included as predictors. The *Skull length* was included in the models on telomere length  
224 to control for any age-related difference among chicks. PFAS were  $\log_{10}$  transformed.

225           Data transformation was done to meet model assumptions as homoscedasticity and normality of  
226 residuals, further confirmed by visually inspecting Q-Q plots (not achieved in the models in yellow-legged  
227 gulls likely due to the small sample size ( $n=11$ ) and the high variation in concentrations for these  
228 contaminants). All data transformation and violation of models' assumptions are reported throughout the  
229 manuscript. Statistical significance was set to  $\alpha=0.05$  and 95% confidence intervals were used during data  
230 processing and data visualization. A complete list of the models used in the present study can be found in  
231 the supporting information. All statistical analyses were performed using R version 3.5.2.

232

## 233 **Results**

234 PFAS concentrations are summarized in Table 1 and Figure 1, and their detection frequency is  
235 reported in Table S1.  $\Sigma$ PFAS ranged from an average of 26.09 ng/g in males to 32.26 ng/g in females in  
236 herring gulls; an average of 34.95 ng/g in males to 37.84 ng/g in females in lesser black-backed gulls; an  
237 average of 26.77 ng/g in females to 28.80 ng/g in males in great black-backed gulls; and an average of 33.79  
238 ng/g in males to 42.11 ng/g in females in yellow legged gulls.  $\Sigma$ PFAS was mostly represented by L-PFOS,  
239 which was the most abundant PFAS in all species (above 60% in all species, Table 1), having concentrations  
240 about 10 times higher than the other PFAS. Concentrations were as follows: in herring gulls L-PFOS > PFHxS  
241 > Br-PFOS > PFUnDA > PFNA > PFDA > PFTTrDA > PFDoDA > PFTeDA > PFHpS; in lesser black-backed gulls L-  
242 PFOS > PFUnDA > Br-PFOS > PFHxS > PFTTrDA > PFDA > PFNA > PFDoDA > PFTeDA > PFHpS; in great black-  
243 backed gulls L-PFOS > Br-PFOS > PFTTrDA > PFUnDA > PFDA > PFHxS > PFDoDA > PFNA > PFTeDA > PFHpS;  
244 and in yellow-legged gulls L-PFOS > Br-PFOS > PFDA > PFUnDA > PFTTrDA > PFNA > PFHxS > PFDoDA >  
245 PFTeDA > PFHpS. There were no significant differences between sexes in each species for all analysed PFAS  
246 (all  $p \geq 0.07$ , Table 1), nor between PFAS levels between 2016 and 2018 (all  $t < 2.79$ , all  $p > 0.08$ ) except for  
247 PFHpS, which was higher in 2016 than 2018 in great black-backed gulls ( $t = 3.15$ ,  $p = 0.03$ ).

248 There were statistically significant differences among species for most carboxylic and sulfonic PFAS  
249 (Figure 1, Table S3). Among perfluoroalkyl carboxylic acids, PFUnDA was higher in lesser black-backed gulls  
250 than great black-backed gulls and herring gulls (both  $t > 2.75$ , both  $p < 0.05$ ; Figure 1, Table S3); PFDoDA was  
251 higher in both lesser and great black-backed gulls than herring gulls (both  $t > 3.24$ , both  $p < 0.01$ ; Figure 1,  
252 Table 3); PFTTrDA and PFTeDA were higher in both lesser and great black-backed gulls than herring gulls (all  
253  $t > 3.41$ , all  $p < 0.01$ ; Figure 1, Table S3), and were also higher in great black-backed gulls than lesser black-  
254 backed gulls (both  $t > 2.65$ , both  $p < 0.05$ ; Figure 1, Table S3). Among sulfonic acids, PFHxS was highest in  
255 herring gulls (both  $t > 4.60$ , both  $p < 0.001$ ; Figure 1, Table S3); PFHpS was higher in herring gulls than great  
256 black-backed gulls ( $t = 3.28$ ,  $p < 0.01$ ; Figure 1, Table S3); and L-PFOS was highest in lesser black-backed gulls  
257 (both  $t > 2.91$ , both  $p < 0.05$ ; Figure 1, Table S3). Yellow-legged gull chicks showed the highest average levels

258 of PFNA, PFDA, PFDoDA, Br- and L-PFOS when visually comparing them with the other species (Figure 1),  
259 although this was not statistically tested due to the different years of sampling.

260 TT3 was similar between 2016 and 2018 (all  $t < 2.04$ , all  $p > 0.34$ ) and between males and females (all  
261  $t > 1.38$ , all  $p > 0.99$ ) in each species. In herring gull males, TT3 was significantly and negatively associated  
262 with PFDA and PFDoDA ( $t = -2.40$ ,  $p = 0.02$  and  $t = -2.00$ ,  $p = 0.05$ , respectively; Figure 2, Table S4), and showed a  
263 non-significant tendency to be negatively associated with PFUnDA and PFTeDA ( $t = -1.83$ ,  $p = 0.07$ , and  $t = -$   
264  $1.87$ ,  $p = 0.07$ , respectively, Table S4). In herring gull females, TT3 was positively associated with PFTeDA  
265 ( $t = 2.26$ ,  $p = 0.03$ ; Figure 2, Table S4). TT3 was also positively associated with PFDoDA ( $t = 2.24$ ,  $p = 0.03$ , Figure  
266 2, Table S4) in great black-backed gulls, and showed a non-significant tendency to be positively associated  
267 with PFUnDA ( $t = 1.70$ ,  $p < 0.10$ , Table S4), while it was positively associated with PFTeDA in lesser black-  
268 backed gulls independently of the sex of the birds ( $t = 2.06$ ,  $p < 0.05$ ; Figure 2, Table S4).

269 There was no association between telomere length and skull length in any of the study species (all  
270  $t < 1.43$ , all  $p > 0.18$ ). Telomere length was similar between 2016 and 2018 in all species (all  $t < 0.46$ , all  $p > 0.99$ ,  
271 not tested in yellow-legged gulls for which we only had 2019 data), and between males and females (all  
272  $t < 0.89$ , all  $p > 0.39$ ) in all four species. Among the three species, telomere length showed a non-significant  
273 tendency to be negatively associated with PFDA, PFHpS, Br- and L-PFOS (all  $t < -1.81$ , all  $p < 0.10$ ; Table S5) in  
274 great black-backed gull chicks.

275 There was no difference in BMI between males and females (all  $t < 1.82$ , all  $p > 0.46$ ) and between  
276 sampling years (all  $t < 0.45$ , all  $p > 0.99$ ) in each species. BMI was similar among species (all  $t = -2.01$ , all  
277  $p > 0.10$ ) and between sexes in yellow-legged gulls (run on separated models; both  $t < 0.89$  both  $p > 0.39$ ). BMI  
278 was negatively correlated with PFDA, Br-PFOS and L-PFOS in great black-backed gull females (all  $t < -2.15$ , all  
279  $p \leq 0.04$ , Figure 3, Table S6). In lesser black-backed gull males, BMI was negatively associated with L-PFOS  
280 ( $t = -2.10$ ,  $p = 0.04$ , Figure 3, Table S6) and showed a non-significant tendency to be negatively associated  
281 with Br-PFOS ( $t = -1.90$ ,  $p = 0.06$ , Table S6). BMI also showed a general negative association with PFNA and  
282 PFHpS independently of the sex of the birds and the considered species (both  $t < -2.49$ , both  $p \leq 0.02$ , Figure  
283 3, Table S6).

284 Separated models on yellow-legged gull chicks showed a significant positive association between  
285 telomere length and L-PFOS ( $t=2.68$ ,  $p=0.04$ , Figure 4, Table S7), and a non-significant tendency to be  
286 positively associated with PFUnDA ( $t=2.34$ ,  $p=0.06$ , Figure 4, Table S7). Separated models on yellow-legged  
287 gull chicks showed a significant negative association between BMI and PFUnDA ( $t=-3.14$ ,  $p=0.01$ , Figure 4,  
288 Table S8), while this association was non-significant with the other PFAS (all  $t<1.77$ , all  $p>0.11$ , Table S8).

289

## 290 **Discussions**

291 Our study investigated the potential disrupting effects of PFAS on body condition, thyroid hormone levels,  
292 and telomere length of chicks from four seabird species from South Western France. By comparing PFAS  
293 concentrations in chicks with those found in the literature from other species and regions, we found that  
294 some chicks are exposed to high concentrations of PFAS. We also found differences in the contamination  
295 patterns among the species, possibly due to the different diet the young receive from their parents. In  
296 lesser and great black-backed gulls, both females and males showed significant negative associations  
297 between several PFAS and their body mass index, indicating that PFAS may interfere with chicks'  
298 development. Our results also corroborate the hypothesis that PFAS may impact on the physiological status  
299 of seabirds, as there were significant associations between several PFAS and the plasma concentrations of  
300 TT3 (both negative and positive depending on the studied species), and a positive association between  
301 telomere length and L-PFOS in the yellow-legged gull.

302 Our study is amongst the first to report the concentrations of PFAS in chicks of several seabird  
303 species from Europe. Among perfluoroalkyl carboxylic acids, the odd carbon numbered PFUnDA and  
304 PFTrDA were the most abundant, a pattern commonly found in other species as the glaucous gull (Melnes  
305 et al., 2017) and the kittiwakes (Tartu et al., 2014) from the Arctic. The levels of perfluoroalkyl carboxylic  
306 acids found in this study (ranging from a mean of 0.2 ng/g of PFTeDA in herring gulls to 2.1 ng/g of PFUnDA  
307 in great black-backed gulls) are generally lower than what has been found in adult birds from the same  
308 study area (ranging from a mean of 0.6 ng/g of PFNA in herring gulls to a mean of 6.9 ng/g of PFTrDA in  
309 great black-backed gulls; Sebastiano et al. 2021). These concentrations are similar to PFAS in a population  
310 of flamingo *Phoenicopterus roseus* chicks from the Ebro Delta in Spain (except for PFOA, which showed an

311 average concentration of 38.5 ng/mL; Dulsat-Masvidal et al., 2023), and lower than black-legged kittiwake  
312 adults from Svalbard (ranging from a mean of 1.0 ng/g of PFNA to 18.2 ng/g of PFTTrDA; Tartu et al., 2014).  
313 Comparably to carboxylic acids, the concentration of perfluoroalkyl sulfonic acids in chicks reflected what is  
314 often found in seabird studies, with L-PFOS concentrations representing over 65% of the total PFAS  
315 concentration, followed by Br-PFOS, PFHxS, and PFHpS. As food represents the main pathway of exposure  
316 to environmental contaminants in seabirds (Lavoie et al., 2013), chicks largely reflects the accumulation  
317 through the food brought by the parents, showing contaminant concentrations that are usually lower than  
318 those found in adult birds because the temporal window for bioaccumulation is much shorter (Sebastiano  
319 et al., 2016; Sebastiano et al., 2017). While all species showed highest L-PFOS concentrations followed by  
320 Br-PFOS, PFHxS, and PFHpS, reflecting the results on adult birds (Sebastiano et al., 2021), herring gull chicks  
321 surprisingly exhibited higher levels of PFHxS in comparison with the other species, concentrations that are  
322 also higher than what has been found in herring gull adults from the region (Sebastiano et al., 2021). As  
323 bird eggs commonly contain very low level of PFHxS compared with other PFAS (Groffen et al., 2017;  
324 Jouanneau et al., 2022a; Verreault et al., 2005), one possible explanation might be that the other species  
325 fed their young with a higher proportion of eggs than herring gulls have, resulting in lower levels of blood  
326 PFHxS. However, it also should be noted that previous work on the same seabird populations found that  
327 the isotopic niche of chicks (inferred from nitrogen and carbon stable isotopes), highly overlapped among  
328 the four studied species (Jouanneau et al. 2022b). Therefore, except the observed small inter-individual  
329 variation in the way chicks are fed by their parents (Jouanneau et al. 2022b), other factors like excretion  
330 and/or assimilation mechanisms, may also drive the observed concentrations.

331 As stated above, L-PFOS was the PFAS showing concentrations of concern (from ~17ng/g to  
332 ~30ng/g average PFOS concentration depending on the species), similar to those found in adult great black-  
333 backed gulls from Norwegian populations (Bustnes et al., 2008), and lower than those found in the  
334 Audouin's gull *Larus audouinii* and yellow-legged gull from the Ebro Delta in Spain (from ~25ng/g to  
335 ~61ng/g average PFOS concentration in adults; Bertolero et al., 2015). Such concentrations are also several  
336 times lower than those reported in the lesser black-backed gull chicks samples 50 km away from a  
337 fluorochemical plant in Antwerp, Belgium (average of 160 ng/mL in 4-week-old chicks; Lopez-Antia et al.,

2021), and from bald eagle *Haliaeetus leucocephalus* chicks from upper Midwestern United States located closely to a 3M fluorochemical plant (averages of different sampling sites ranging from 77 ng/mL to 800 ng/mL; Route et al., 2014). Although there are limited toxicity data for fluorinated compounds in birds, previous work in northern bobwhites quail *Colinus virginianus* estimated a LOAEL (lowest observed adverse effect level) of 11.6 ng/g of PFOS in liver samples of juveniles (Dennis et al. 2022). Considering a liver to whole-blood ratio of 2.72 for PFOS (as previously documented in chicks of several seabird species; Robuck et al. 2021), and assuming that plasma is about 50% of whole-blood (and therefore a liver to plasma ratio of 1.36 for PFOS), almost all sampled chicks exceed such 11.6 ng/g threshold effect. Deriving toxicity data from other studies (and from unrelated species) is, however, highly debatable since the effects are often species-specific (Sebastiano et al. 2022), thus these comparisons should be interpreted with caution. In birds - and more specifically, seabirds - the availability of toxicity data for many PFAS alone, and in combination with each other, remains very limited so far, thus we encourage future studies to seek to clarify this aspect.

The majority of studies that have investigated the presence of PFAS have been often carried out on adult birds, so these concentrations are also difficult to place in an ecotoxicological context as several other environmental factors, the health status of birds, and the concomitant exposure to other contaminants may enhance the susceptibility of individuals to a specific stressor (Sebastiano et al., 2022). Therefore, some PFAS may be associated with adverse health effects even when they occur at a lower concentration than other PFAS. Our results show that herring gull females with higher levels of PFTeDA have higher TT3 concentrations. Similarly, PFDoDA and PFTrDA were positively associated with TT3 in great black-backed gull males and lesser black-backed gulls, respectively. These positive associations with thyroid hormones are similar to what has been found in glaucous gull adult females (PFOS and free triiodothyronine (FT3); Melnes et al., 2017), in northern fulmar *Fulmarus glacialis* chicks (PFHpS, PFOS, PFNA, and total thyroxin (TT4); Nøst et al., 2012), and adult kittiwakes (L-PFOS, PFDA, and TT4 in males, PFDoDA, PFTrDA, PFTeDA and TT3 in females; Ask et al., 2021) from Svalbard, and in adult great black-backed gull females from France (PFUnDA, PFDoDA, PFTrDA, PFTeDA and Br-PFOS and TT3; Sebastiano et al., 2021). This positive association may be the result of an alteration of the hypothalamic-pituitary-thyroid (HPT) axis with the

365 consequent up-regulation of thyroid hormone receptors (reviewed in Coperchini et al., 2020). However, we  
366 also found that herring gull chicks exposed to higher concentrations of PFDA and PFDoDA showed the  
367 lowest TT3 concentration. To the best of our knowledge, this is the first study to report a negative  
368 association between PFAS and thyroid hormones in chicks, as such associations were only recently reported  
369 in adult great black-backed gull males (PFHxS and TT3; Sebastiano et al., 2021) and thick-billed murre males  
370 (PFOS, PFDoA, PFTeDA, and TT3; Choy et al., 2022). The maintenance of optimal levels of thyroid hormones  
371 is of fundamental importance for development (McNabb, 2007), and an interference in the HPT axis, which  
372 regulates the thyroid hormone cascade, could cause lasting effects in affected individuals (McNabb, 2007).  
373 Previous work in rodents showed that PFAS (i.e. PFHxS) can indeed induce developmental toxicity through a  
374 reduction in thyroxin levels (Ramhøj et al., 2018). In humans and laboratory studies on cell cultures, PFAS  
375 are known to interfere with the endocrine system and to reduce the production of T3 and T4, for instance,  
376 by depressing iodide peroxidase activity or by inhibiting iodine accumulation in thyroid cells (reviewed in  
377 Coperchini et al., 2020). Despite the recent findings suggesting a possible disruption of thyroid hormone  
378 levels in birds and other animals, our understanding of the underlying mechanisms remains very limited  
379 although it should represent a current priority. Because PFAS and thyroid hormones bind with plasma  
380 proteins (e.g. albumin; Forsthuber et al. 2020; McNabb 2007), the associations we found between TT3 and  
381 specific PFAS may also be associated with a difference in plasma protein concentrations in the studied  
382 birds. Birds with low plasma protein concentrations would therefore have low concentrations of both PFAS  
383 and thyroid hormones, and vice versa. Information on the free fraction of thyroid hormones in the plasma  
384 would also be highly beneficial in the present study to assess the importance of binding site competition  
385 between PFAS and thyroid hormones as an explanation for the observed associations. It also remains  
386 unclear why males and females seem to respond differently to the same stimulus even in chicks, as in our  
387 study, i) females showed similar levels than males in terms of absolute PFAS concentrations; ii) chicks do  
388 not show sexual dimorphism, a condition which in adults may affect their physiological status and their  
389 response to contaminant exposure; and iii) one of the sexes may be more susceptible at certain life stages  
390 in adults (e.g. reproduction in females, which is highly costly, Hanssen et al., 2005), which does not,  
391 however, apply to chicks.



392           Despite the known importance of studying telomere length in relation to contaminant levels in wild  
393 animals (Louzon et al. 2019), until a few years ago we knew almost nothing about the possible association  
394 between PFAS and telomeres. Sea eagle chicks failed to show any association (Sletten et al., 2016), but a  
395 positive association between PFAS and telomeres was found in kittiwakes (Blévin et al., 2017a) and in the  
396 glaucous gull (Sebastiano et al. 2020). In the present study, despite the relatively small sample size in  
397 yellow-legged gulls, we found a positive association between L-PFOS levels and telomere length, suggesting  
398 that chicks with the highest L-PFOS concentrations also have longer telomeres. One possible explanation  
399 for the positive associations between PFAS and telomere length (or the change in telomere length over  
400 time) may be related to the up-regulation of the activity of the telomerase, the enzyme responsible for  
401 maintenance of the length of telomeres. For instance, if PFAS impact on the hormones that regulate the  
402 activity of telomerase (directly by modulating its activity, or by decreasing the concentration of telomerase-  
403 inhibitory hormones), higher PFAS concentrations would result in longer telomeres, although evidence of  
404 such association is lacking. One alternative explanation for this PFAS - telomere association may lie in the  
405 nutritional status of the birds. Although yellow-legged gull adults from the study area show a generalist diet  
406 (Jouanneau et al., 2022b), the chicks included in this study are fed with high trophic level food of marine  
407 origin as highlighted by the high carbon and sulphur stable isotope values (Jouanneau et al., 2022b). If the  
408 high L-PFOS concentrations have no negative effect on the chicks of this species (given the absence of  
409 negative association with other markers), the high-quality diet they receive may actually have a beneficial  
410 effect on their physiology, including telomere length. This hypothesis needs to be specifically tested as it  
411 would suggest that under certain conditions (i.e., environmental contamination not being excessively  
412 elevated or species being particularly tolerant), the potential detrimental effects of PFAS exposure through  
413 food is negligible compared to the benefits of a high trophic level diet.

414           This potential positive association between food quality and telomere length is, however,  
415 contrasted by the results of the association between PFAS and body condition. The general negative  
416 association between the body condition of chicks and PFNA and PFHpS, together with the negative  
417 associations specifically found with PFDA, Br-PFOS, and L-PFOS in female great black-backed gull, with L-  
418 PFOS in male lesser black-backed gull, and with PFUnDA in yellow-legged gull, strongly suggest that

419 exposure to PFAS impacts on growth of developing seabirds. PFAS may alter the expression of genes  
420 involved in the metabolism of lipids and fatty acids (Jacobsen et al., 2018) and induce adipogenesis (Xu et  
421 al., 2016). Although our results are not in line with those found previously in male kittiwakes (Tartu et al.,  
422 2014), they overlap with what has been found in adult birds of the same species from the same geographic  
423 area (Sebastiano et al., 2021). Furthermore, it is also necessary to take into account that PFASs can affect  
424 several physiological mechanisms as altering the levels of thyroid and steroid hormones (Coperchini et al.,  
425 2020; Liu et al., 2020), thereby impacting on energy expenditure and metabolism (Blévin et al., 2017b).  
426 Considering that those results were found in almost all studied species, and were all showing the same  
427 pattern, we suggest that exposure to PFAS early in life may ultimately reduce the body condition of birds.  
428 Given that we have limited understanding on this relationship, especially in developing birds, and given that  
429 the directions of these associations appear to be species-specific, this aspect clearly warrants further  
430 investigation.

431

## 432 **Conclusions**

433 Our study provides the first data on PFAS levels in chicks of several seabird species from Europe, during  
434 their developmental period. Some PFAS showed comparable levels to other seabird species and lower  
435 levels than adult birds from the same species and the same study area. However, in lesser and great black-  
436 backed gulls, both females and males showed significant negative associations between several PFAS and  
437 their body mass index, indicating that PFAS may impact on the health status of exposed individuals and  
438 therefore pose a threat to long-lived seabirds. The hypothesis that PFAS may impact on the physiological  
439 status of seabirds is further corroborated by the significant associations between PFAS and the plasma  
440 concentrations of TT3 and telomere length (both negative and positive depending on the studied species).

441 These results assume even greater importance considering that they were found in chicks, and  
442 need to be seriously considered as PFAS may interfere with their physiological status during the  
443 developmental period and cause long-lasting consequences. We stress once again how even low  
444 contaminant concentrations may be associated with a physiological response in animals, and that each  
445 species or population reacts differently to stimuli. There is now a large body of evidence showing

446 associations between PFAS and physiological disruption in a variety of organisms, including seabirds. The  
447 experimental investigation of the mechanisms through which PFAS interfere with physiological and  
448 organism functioning need to represent a priority of ecotoxicological studies as this remains a largely  
449 unexplored area of research in wildlife.

450

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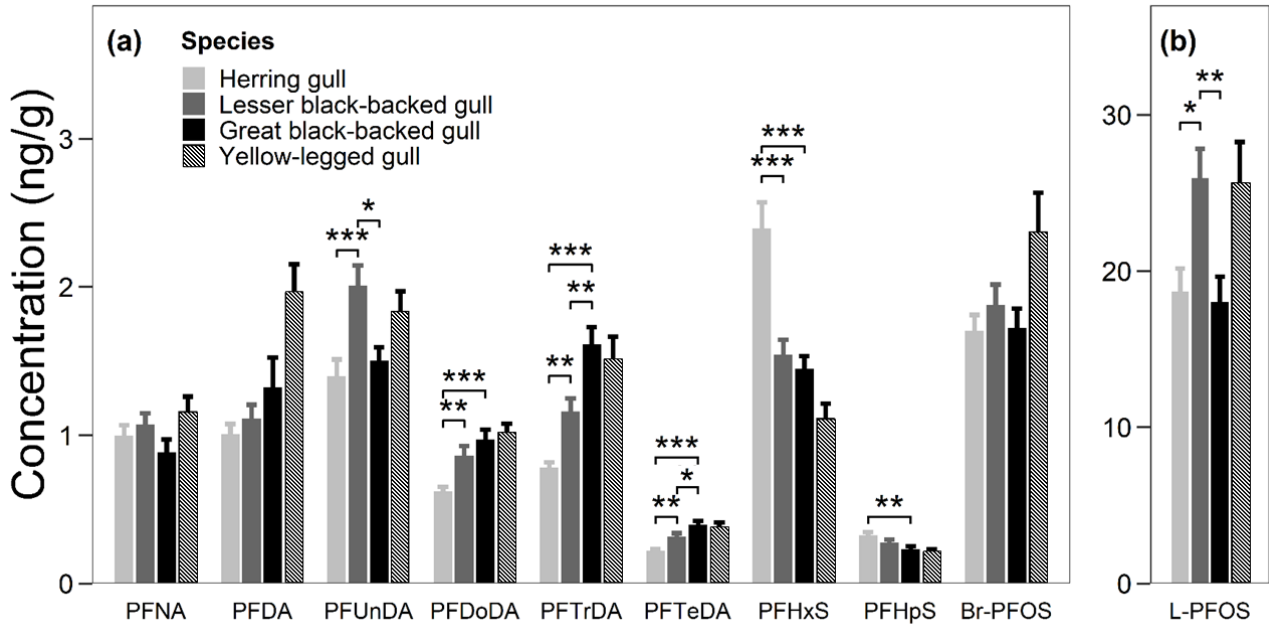
465 **Table 1:** Plasma PFAS concentrations (ng/g of ww) in females and males of the four gull species from South  
 466 Western France. The % refers to the percentage of contribution of each PFAS, while t- and p-values refer to  
 467 the difference in PFAS between females and males. Significant p-values are bolded.

<b>Herring gull <i>Larus argentatus</i></b>								
	<b>Females</b>			<b>Males</b>			<b>t-value</b>	<b>p-value</b>
	<b>mean ± SE</b>	<b>median (range)</b>	<b>%</b>	<b>mean ± SE</b>	<b>median (range)</b>	<b>%</b>		
PFNA	1.19 ± 0.07	1.17 (0.67 - 2.02)	3.7%	0.90 ± 0.01	0.86 (0.45 - 1.22)	3.5%	1.57	0.62
PFDA	1.09 ± 0.05	1.04 (0.64 - 1.63)	3.4%	0.96 ± 0.02	0.95 (0.49 - 1.73)	3.7%	0.83	0.96
PFUnDA	1.59 ± 0.11	1.41 (0.99 - 3.28)	4.9%	1.30 ± 0.02	1.27 (0.70 - 1.80)	5.0%	1.27	0.80
PFDoDA	0.60 ± 0.02	0.51 (0.47 - 0.83)	1.9%	0.63 ± 0.01	0.60 (0.39 - 0.92)	2.4%	-0.17	0.99
PFTTrDA	0.78 ± 0.02	0.72 (0.70 - 1.03)	2.4%	0.79 ± 0.01	0.74 (0.45 - 1.03)	3.0%	0.01	0.99
PFTeDA	0.20 ± 0.01	0.22 (0.13 - 0.27)	0.6%	0.23 ± 0.00	0.21 (0.16 - 0.33)	0.9%	-0.85	0.96
PFHxS	2.46 ± 0.18	2.14 (0.98 - 4.16)	7.6%	2.36 ± 0.04	2.23 (1.45 - 3.20)	9.1%	-0.08	0.99
PFHpS	0.36 ± 0.02	0.40 (0.19 - 0.51)	1.1%	0.30 ± 0.01	0.33 (0.12 - 0.41)	1.2%	1.16	0.85
Br-PFOS	1.96 ± 0.10	1.80 (1.19 - 2.91)	6.1%	1.58 ± 0.02	1.63 (1.00 - 2.12)	6.0%	1.71	0.72
L-PFOS	22.02 ± 1.29	20.28 (12.20 - 36.38)	68.2%	17.04 ± 0.34	17.96 (9.20 - 24.64)	65.3%	1.60	0.61
ΣPFAS	32.26 ± 1.78	29.27 (18.54 - 49.98)		26.09 ± 0.41	28.10 (14.61 - 34.66)		1.41	0.72
<b>Lesser black-backed gull <i>Larus fuscus</i></b>								
PFNA	1.18 ± 0.05	1.13 (0.68 - 1.67)	3.1%	0.99 ± 0.03	0.99 (0.43 - 1.66)	2.8%	0.08	0.99
PFDA	1.25 ± 0.06	1.22 (0.70 - 2.23)	3.3%	1.01 ± 0.03	1.02 (0.47 - 1.42)	2.9%	0.23	0.99
PFUnDA	2.05 ± 0.07	1.85 (1.39 - 3.01)	5.4%	1.98 ± 0.06	1.96 (1.13 - 3.01)	5.7%	0.28	0.99
PFDoDA	0.94 ± 0.04	0.91 (0.47 - 1.59)	2.5%	0.81 ± 0.02	0.80 (0.44 - 1.17)	2.3%	0.22	0.99
PFTTrDA	1.13 ± 0.05	1.02 (0.57 - 1.91)	3.0%	1.19 ± 0.04	1.15 (0.58 - 1.80)	3.4%	-0.27	0.99
PFTeDA	0.36 ± 0.02	0.34 (0.18 - 0.59)	0.9%	0.28 ± 0.01	0.28 (0.15 - 0.42)	0.8%	0.84	0.96
PFHxS	1.67 ± 0.03	1.67 (1.35 - 2.00)	4.4%	1.45 ± 0.05	1.39 (0.69 - 2.54)	4.1%	0.19	0.99
PFHpS	0.28 ± 0.01	0.27 (0.21 - 0.40)	0.7%	0.27 ± 0.01	0.24 (0.14 - 0.48)	0.8%	0.20	0.99
Br-PFOS	1.89 ± 0.06	1.74 (1.37 - 2.75)	5.0%	1.87 ± 0.06	1.83 (0.97 - 3.37)	5.4%	0.50	0.98
L-PFOS	27.09 ± 0.98	27.11 (16.23 - 40.40)	71.6%	25.10 ± 0.80	22.25 (13.52 - 42.43)	71.8%	0.14	0.99
ΣPFAS	37.84 ± 1.34	37.00 (23.31 - 56.23)		34.95 ± 1.01	32.85 (19.07 - 56.45)		0.15	0.99
<b>Great black-backed gull <i>Larus marinus</i></b>								
PFNA	0.75 ± 0.03	0.73 (0.58 - 0.96)	2.8%	0.96 ± 0.04	0.80 (0.46 - 1.63)	3.3%	-1.06	0.89
PFDA	1.00 ± 0.04	0.96 (0.78 - 1.37)	3.7%	1.50 ± 0.09	1.21 (0.44 - 3.48)	5.2%	-1.79	0.48
PFUnDA	1.49 ± 0.04	1.56 (1.17 - 1.73)	5.6%	1.51 ± 0.04	1.52 (0.88 - 2.05)	5.2%	-0.10	0.99
PFDoDA	0.96 ± 0.02	0.96 (0.83 - 1.14)	3.6%	0.98 ± 0.03	0.88 (0.61 - 1.68)	3.4%	-0.12	0.99
PFTTrDA	1.80 ± 0.05	1.77 (1.48 - 2.34)	6.7%	1.51 ± 0.05	1.43 (0.96 - 2.44)	5.2%	1.41	0.72
PFTeDA	0.42 ± 0.01	0.44 (0.34 - 0.50)	1.6%	0.38 ± 0.01	0.33 (0.24 - 0.67)	1.3%	0.84	0.96
PFHxS	1.41 ± 0.03	1.44 (1.11 - 1.65)	5.3%	1.46 ± 0.04	1.55 (0.59 - 2.08)	5.1%	0.53	0.99
PFHpS	0.22 ± 0.01	0.21 (0.14 - 0.33)	0.8%	0.24 ± 0.01	0.23 (0.12 - 0.45)	0.8%	-0.75	0.97
Br-PFOS	1.65 ± 0.05	1.59 (1.27 - 2.03)	6.2%	1.76 ± 0.06	1.75 (0.79 - 3.22)	6.1%	-0.57	0.99
L-PFOS	17.06 ± 0.62	17.11 (12.20 - 22.19)	63.7%	18.50 ± 0.74	18.91 (8.02 - 36.14)	64.2%	-0.62	0.99
ΣPFAS	26.77 ± 0.77	27.06 (21.32 - 32.91)		28.80 ± 0.97	30.03 (14.01 - 51.24)		-0.61	0.99
<b>Yellow-legged gull <i>Larus michahellis</i></b>								
PFNA	1.25 ± 0.05	1.17 (1.03 - 1.58)	3.0%	1.10 ± 0.06	1.19 (0.44 - 1.62)	3.3%	0.86	0.41
PFDA	2.00 ± 0.07	2.16 (1.51 - 2.36)	4.8%	1.94 ± 0.12	1.82 (0.95 - 3.18)	5.7%	0.47	0.65
PFUnDA	2.07 ± 0.12	1.92 (1.32 - 2.84)	4.9%	1.67 ± 0.03	1.64 (1.40 - 2.11)	5.0%	1.45	0.18
PFDoDA	1.15 ± 0.04	1.15 (0.86 - 1.38)	2.7%	0.93 ± 0.02	0.99 (0.63 - 1.10)	2.8%	2.00	0.07*
PFTTrDA	1.72 ± 0.12	1.76 (0.83 - 2.47)	4.1%	1.36 ± 0.07	1.36 (0.62 - 1.97)	4.0%	1.02	0.33
PFTeDA	0.45 ± 0.02	0.49 (0.29 - 0.53)	1.1%	0.33 ± 0.01	0.34 (0.15 - 0.44)	1.0%	1.76	0.11
PFHxS	1.32 ± 0.05	1.21 (1.10 - 1.70)	3.1%	0.97 ± 0.04	1.14 (0.39 - 1.24)	2.9%	1.76	0.11
PFHpS	0.24 ± 0.01	0.24 (0.17 - 0.31)	0.6%	0.19 ± 0.01	0.20 (0.13 - 0.25)	0.6%	1.85	0.09
Br-PFOS	2.49 ± 0.13	2.41 (1.70 - 3.41)	5.9%	2.29 ± 0.16	1.93 (1.28 - 4.62)	6.8%	0.65	0.53
L-PFOS	29.41 ± 2.44	26.26 (15.98 - 44.45)	69.8%	22.99 ± 0.76	21.26 (18.09 - 32.22)	68.1%	1.04	0.32
ΣPFAS	42.11 ± 2.93	38.47 (26.17 - 60.42)		33.79 ± 0.95	30.94 (25.97 - 45.23)		1.15	0.28

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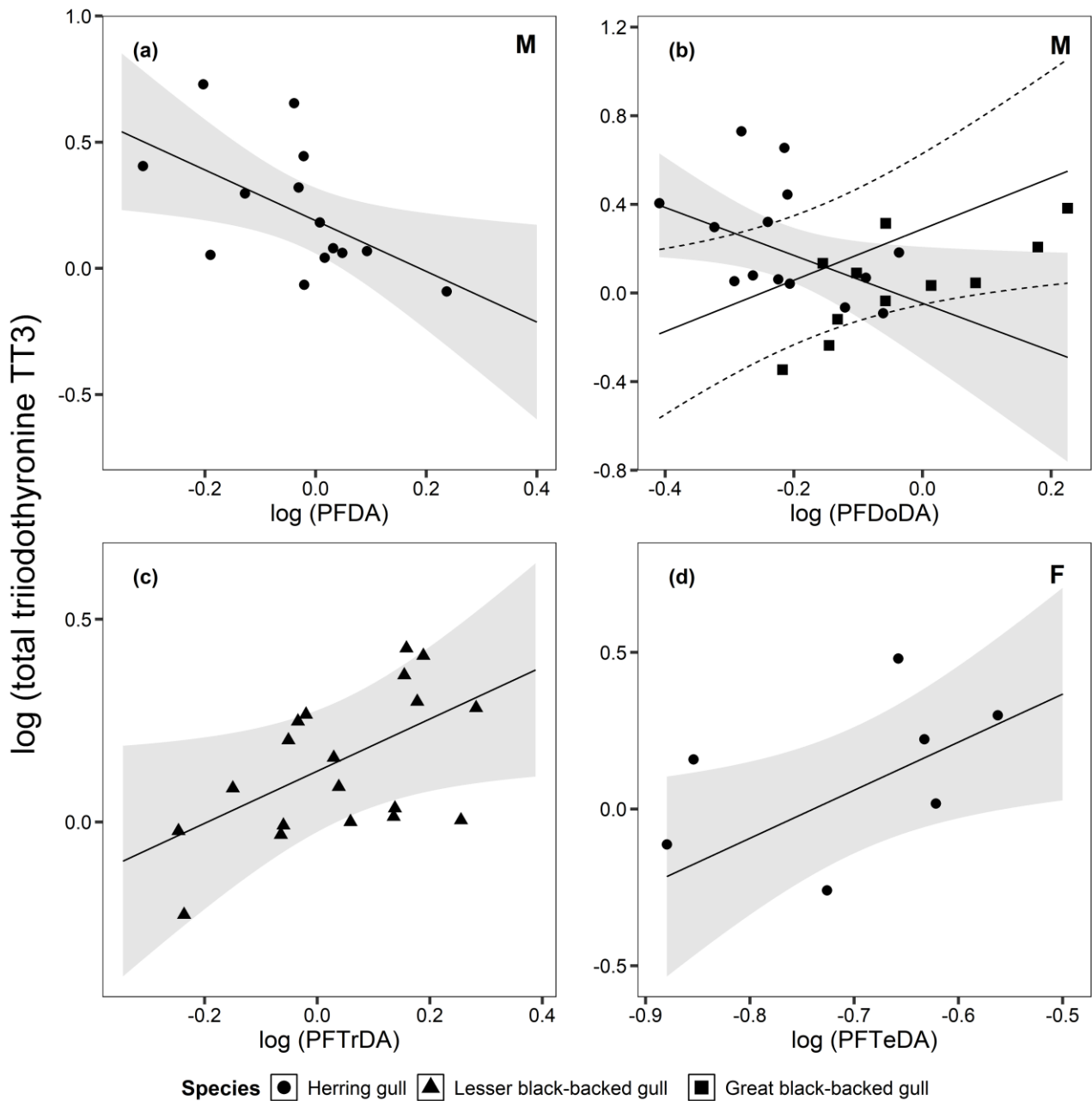
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474 **Figure 1.** Plasma concentrations of PFAS (expressed as ng/g of ww) in the four gull species from South  
475 Western France. Statistically significant differences are indicated by the asterisks \*, \*\*, \*\*\*, which indicate  
476 a p-value < 0.05, <0.01, and <0.001, respectively. Yellow-legged gulls were sampled in a different year  
477 (2019) than the other species (2016 and 2018), thus statistical comparisons with the other species were not  
478 carried out.

479

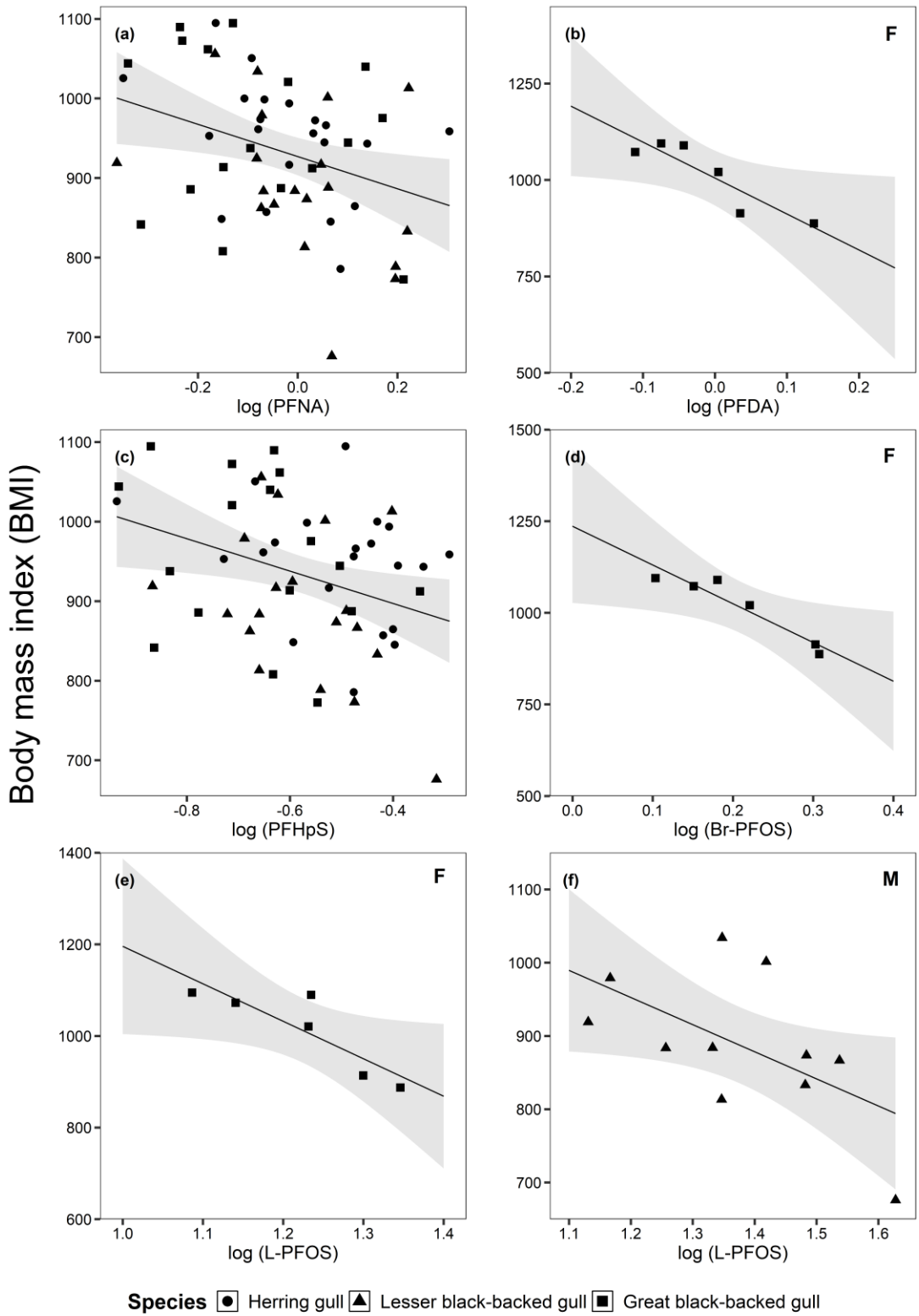


480

481 **Figure 2.** Relationship between the concentration of the log-transformed TT3 and PFAS (PFDA, PFDODA,  
 482 PFTrDA, PFTeDA; panel a to d, respectively), of the three seabird species from Ile de Re. Shapes of data  
 483 points are used to distinguish each species, and the solid line represents the trend. When more than a  
 484 single significant relationship occurs, polygons (representing 95% confidence intervals) following the first  
 485 one are bounded by a dotted line. Data refer to the period 2016 and 2018 for which both TT3 and PFAS  
 486 were available (n = 57).

487

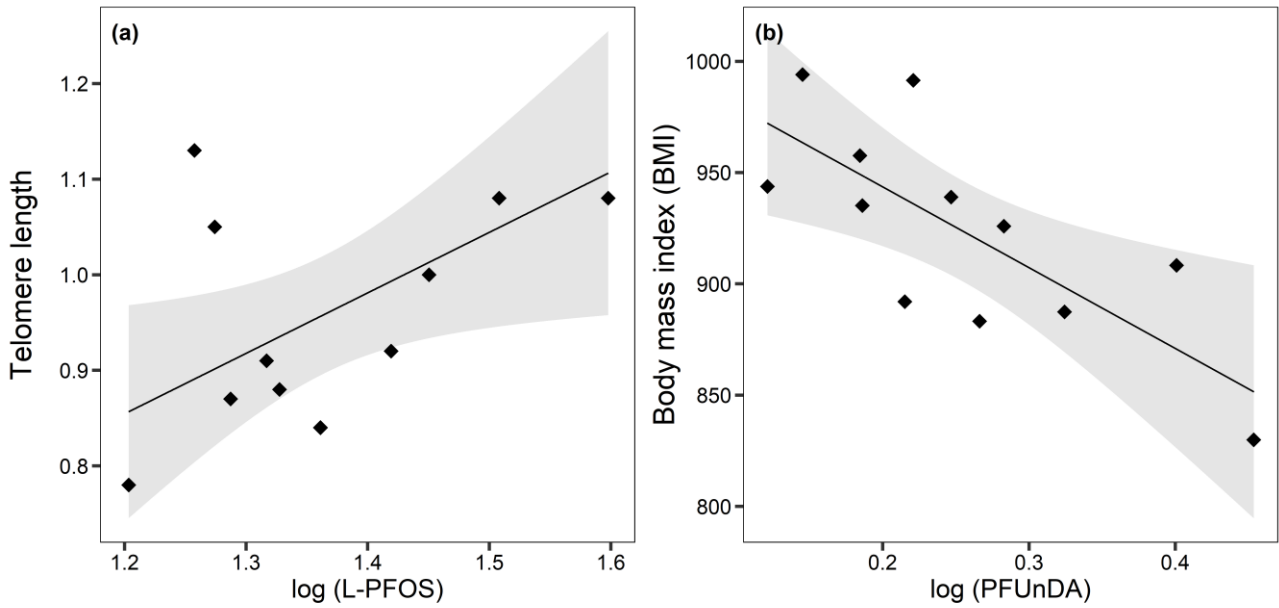
488



489

490 **Figure 3.** Relationship between the body mass index BMI and PFAS (PFNA, PFDA, PFHpS, Br-PFOS, and L-  
 491 PFOS; panel a to f, respectively), of the three seabird species from Ile de Re. Shapes of data points are used  
 492 to distinguish each species, and the solid line represents the trend. Polygons represent 95% confidence  
 493 intervals. Data refer to the period 2016 and 2018 for which both BMI and PFAS were available (n = 58).

494



495

496 **Figure 4.** Relationship between (a) telomere length and L-PFOS and (b) BMI and PFUnDA in yellow-legged  
497 gull chicks from Ile de Re. The solid line represents the trend while the polygon represents 95% confidence  
498 intervals. Data refer to the year 2019 for which both telomere length and PFAS (n=11) and BMI and PFAS  
499 data (n=12) were available in this species.

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