Environmental Science & Technology

pubs.acs.org/est

Article

A Bad Start in Life? Maternal Transfer of Legacy and Emerging Poly- and Perfluoroalkyl Substances to Eggs in an Arctic Seabird

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Cite This: *Environ. Sci. Technol.* 2022, 56, 6091−6102

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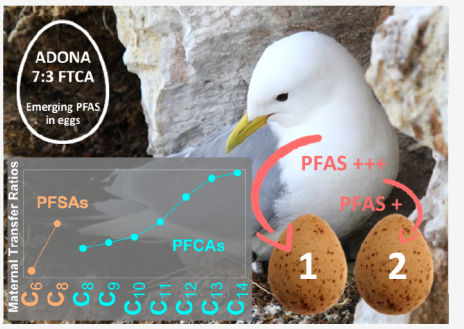
ABSTRACT: In birds, maternal transfer is a major exposure route for several contaminants, including poly- and perfluoroalkyl substances (PFAS). Little is known, however, about the extent of the transfer of the different PFAS compounds to the eggs, especially for alternative fluorinated compounds. In the present study, we measured legacy and emerging PFAS, including Gen-X, ADONA, and F-53B, in the plasma of prelaying black-legged kittiwake females breeding in Svalbard and the yolk of their eggs. We aimed to (1) describe the contaminant levels and patterns in both females and eggs, and (2) investigate the maternal transfer, that is, biological variables and the relationship between the females and their eggs for each compound. Contamination of both females and eggs were dominated by linPFOS then PFUnA or PFTriA. We notably found 7:3 fluorotelomer carboxylic acid—a precursor of long-chain carboxylates—in 84% of the egg yolks, and provide the first documented finding of ADONA in wildlife. Emerging compounds were all below the detection limit in female plasma. There was a linear association between females and eggs for most of the PFAS. Analyses of maternal transfer ratios in females and eggs suggest that the transfer is increasing with PFAS carbon chain length, therefore the longest chain perfluoroalkyl carboxylic acids (PFCAs) were preferentially transferred to the eggs. The mean $\sum_{PFAS}$ in the second-laid eggs was 73% of that in the first-laid eggs. Additional effort on assessing the outcome of maternal transfers on avian development physiology is essential, especially for PFCAs and emerging fluorinated compounds which are under-represented in experimental studies.



KEYWORDS: *black-legged kittiwake, Rissa tridactyla, top predator, Svalbard, PFAS, emerging contaminants*

INTRODUCTION

Poly- and perfluoroalkyl substances (PFAS) are synthetic chemicals widespread globally.[1] Since the 1950s, thousands of compounds were developed in this family and used in a multitude of manufactured products (firefighting foams, waterproof clothing, nonstick cookware, coatings, food packaging, personal care products, dental floss, electronics, metal plating, and even pesticides) owing to their extremely stable chemical structure and their surfactant properties. After they have been revealed as ubiquitous and toxic for organisms in the early 2000s, some of the historical most noxious compounds such as perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) were phased out by the main manufacturers and recommended for elimination by the Stockholm Convention on Persistent Organic Pollutants.[2−5]

Some of the PFAS bioaccumulate in organisms and biomagnify along trophic chains, particularly in aquatic ecosystems.[6,7] As a consequence, high trophic level aquatic organisms including seabirds often have elevated tissue concentrations.[1,8] Oceanic and atmospheric transport can contribute to the long-range dispersal of PFAS, their precursors, and breakdown products[9−15] which are found in wildlife tissues worldwide, including remote areas like the Arctic.[8,16]

In birds, during egg formation, the female transfers various substances required to enable and sustain the development of the embryo. However, in addition to essential compounds such as water, minerals, proteins, lipids, vitamins, antibodies, or hormones, some contaminants may also be transferred. Persistent organic pollutants (POPs) have been shown to be transferred from mothers to eggs due to their physicochemical properties, via either lipids (e.g., polychlorinated biphenyls (PCBs), pesticides) or proteins (PFAS).[17] Therefore, the avian egg is considered as a relevant monitoring tool for a selection of organic contaminants exposure in many species, as its composition directly reflects that of maternal tissues.[18] However, the few field studies concurrently comparing

Special Issue: Emerging Contaminants: Fluorinated Alternatives to Existing PFAS Compounds

Received: June 9, 2021
Revised: November 8, 2021
Accepted: November 24, 2021
Published: December 7, 2021

variability in, for instance, PCBs and organochlorine pesticides concentrations and composition in both eggs and mother tissues, showed that organic contaminants transfer can be influenced by a combination of biological factors (e.g., egg size, egg mass, egg laying order, number of eggs in clutch, age of the female) and by the physicochemical properties of contaminants.[17] Despite PFAS being studied for almost two decades, their concentrations in eggs have been poorly documented in wildlife, and very few studies evaluated maternal transfers in birds by concurrently measuring PFAS in the eggs and the mother in the field.[19−23] Although fluorinated compounds are transferred at a lower degree than lipophilic contaminants, they can still be found at high concentrations in eggs.[19,24−26] Once accumulated into females, PFAS tend to bind to proteins (especially very low-density lipoproteins) synthesized in the liver, these being then transferred via blood to the ovary and finally to the eggs, and the carbon-chain length has been suggested to be an important driver of PFAS transfer efficiency.[27−29]

In humans and in laboratory models, PFAS can cause cancer, affect immuno-competence, and disrupt the endocrine system.[30] Regarding developing avian embryos, some PFAS compounds were found to be responsible for a lower heart rate, an enlarged liver, thyroid hormones and immune system disruption, as well as a lower hatching success and a lower survival.[31−37] However, the consequences of PFAS exposure remain poorly investigated in wildlife. Recent studies on kittiwakes and other seabirds of the Kongsfjord area suggest that exposure to long-chain perfluorinated carboxylic acids (PFCAs) can be associated with physiological and fitness impairments.[38−43] PFAS cover thousands of substances, the vast majority are not regulated yet and some are increasingly detected in biota.[44] Furthermore, development and manufacturing of alternatives to the legacy PFAS remains largely uncharacterized in terms of risks, despite recent evidence of their environmental occurrence in wildlife tissues.[45,46] Alternative fluorinated compounds are now continuously introduced to the market and despite many of them being still unidentified, some are now known as bioaccumulative.[47] As an example, emerging fluorinated chemicals such as F-53B, ADONA or HFPO−DA (Gen-X) and short-chained precursors are part of these alternative PFAS which have been very scarcely screened for in wildlife before.[48] To the best of our knowledge, to date only three studies detected emerging PFAS in avian eggs.[49−51]

In the present study we aimed to (1) describe concentration and composition of emerging and legacy PFAS in the egg yolk of an Arctic-breeding population of black-legged kittiwakes (*Rissa tridactyla*) facing significant PFAS exposure;[43] (2) investigate the maternal transfer, that is, the relationship between emerging and legacy PFAS found in the eggs yolk with those found in the plasma of the corresponding females sampled during the prelaying stage (i.e., before egg-laying) as well as the effects of biological variable (laying date, clutch size, laying order, female condition). We expect strong correlations of contaminant concentrations between females and their eggs with highly contaminated adults laying highly contaminated eggs, but a decrease in eggs contamination with laying order.[52] We also hypothesize that variations in the transfer of PFAS to the egg should be influenced by the physicochemical properties of the different PFAS compounds, especially the carbon chain length.

MATERIALS AND METHODS

Sample Collection. The study was conducted in a Black-legged kittiwake colony ("Krykkjefjellet" in Kongsfjorden, Svalbard, 78°53′48″N 12°11′43″E) from May to June 2019. On 14 nests, adult females of black-legged kittiwake (hereafter "kittiwakes") were captured a few days before expected laying using a noose at the end of a fishing rod. Females of each nest (n = 14) were individually identified using a numbered metal ring (Stavanger Museum) and a three digits plastic ring to allow individual identification from a distance. Molecular sexing of the adults was performed at the Centre d'Etude Biologiques de Chizé (CEBC), following Fridolfsson and Ellegren (1999).[53] Immediately after capture, a 2 mL blood sample was taken from the alar vein using a heparinized 2.5 mL syringe and a 25G needle. Blood was then transferred in a 2 mL Eppendorf tube and stored in a cooler. At the end of each day, the samples were centrifuged for 10 min. Both tubes of red blood cells (RBC, for molecular sexing) and plasma (for PFAS) were stored in a −20 °C freezer until analyses. The nests corresponding to the sampled birds were then monitored daily using a mirror attached to an 8 m rod. As soon as the first egg was laid, it was collected (n = 14) and replaced by a plastic dummy-egg in order to avoid nest desertion. Similarly, the second-laid egg was collected (n = 11) the day it was laid and the dummy-egg was removed. If they were no second-laid egg after 10 days, the dummy-egg was retrieved. All egg samples were processed in the lab immediately. The eggs were measured (height and diameter) with an electronic caliper and weighted to the nearest 0.01g. Eggs were opened and the yolk and the albumen were separated and stored in 2 mL Eppendorf tubes at −20 °C in a freezer until assayed. All eggs were collected less than 24 h after they were laid, and thus were at a similar development stage, avoiding contaminants to be absorbed by the growing embryo and allowing a comparison between eggs. Sample size was limited by authorization to collect eggs and by the number of accessible nests in the colony. The sampling of birds and eggs was approved by the Governor of Svalbard and by the Norwegian Animal Research Authority (NARA, permit number 19970).

Poly and Perfluoroalkyl Substances Extraction and analysis. We used a method described by Sletten et al. (2016) adapted from Powley et al. (2005) to measure PFAS in females' plasma.[54,55] For yolk samples (∼0.20 g), after mixing methanol and the samples spiked with internal standards (listed in the Supporting Information (SI)), an additional initial step consisting in thoroughly mixing the solution using zirconium beads was added. This step ensured that yolk was completely homogenized with the solvent. PFAS concentrations were only measured in yolk as this is where the most part of these contaminants are located in bird eggs.[21,29] Quantification was conducted by ultrahigh-performance liquid chromatography triple-quadrupole mass spectrometry (UHPLC−MS/MS). The chromatograms were quantified with LCQuan software (version 2.6, Thermo Fisher Scientific Inc., Waltham, MA), applying the isotopic dilution method. An eight-point calibration curve with a concentration range from 0.02 to 10.0 pg μL^{-1} was used. The following "legacy" PFAS were screened in both plasma and yolk: perfluorooctane sulfonamide (FOSA), perfluorobutanesulfonic acid (PFBS), perfluoropentanesulfonic acid (PFPS), perfluorohexanesulfonic acid (PFHxS), perfluoroheptanesulfonic acid (PFHpS), branched perfluorooctanesulfonic acid (brPFOS), linear

https://doi.org/10.1021/acs.est.1c03773
Environ. Sci. Technol. 2022, 56, 6091−6102

Table 1. Descriptive Statistics (Mean ± Standard Deviation SD, Median and Range Min−Max) for PFAS Concentrations (ng g^{-1} ww) in Plasma and Yolk of Black-Legged kittiwakes from Svalbard

	Prelaying females (n = 14)			First-laid eggs (n = 14)			Second-laid eggs (n = 11)		
	mean ± SD	median	min−max	mean ± SD	median	min−max	mean ± SD	median	min−max
PFHxS	0.23 ± 0.09	0.21	0.11−0.40	0.26 ± 0.14	0.26	0.08−0.57	0.22 ± 0.09	0.20	0.08−0.40
brPFOS	0.75 ± 0.49	0.86	0.028−1.38	3.00 ± 1.01	3.12	1.44−4.45	1.93 ± 0.77	1.93	0.88−3.10
linPFOS	10.8 ± 4.70	11.3	3.14−17.42	28.6 ± 10.3	25.9	17.0−50.7	21.3 ± 7.90	19.6	11.8−34.7
PFOA	0.17 ± 0.13	0.14	0.04−0.57	0.23 ± 0.12	0.22	0.04−0.47	0.21 ± 0.08	0.19	0.13−0.41
PFNA	1.06 ± 0.61	1.07	0.19−2.44	1.98 ± 1.07	1.75	0.85−3.64	1.74 ± 0.80	1.48	0.71−2.98
PFDcA	1.71 ± 1.56	1.56	0.40−3.26	3.63 ± 1.88	3.07	1.73−6.83	3.07 ± 1.38	2.60	1.19−5.20
PFUnA	6.88 ± 3.22	7.42	1.40−12.4	17.9 ± 5.78	16.8	10.5−28.6	14.0 ± 4.55	13.4	7.33−20.8
PFDoA	1.78 ± 0.98	1.78	0.02−3.76	6.07 ± 1.46	5.90	4.36−9.41	4.40 ± 1.19	4.55	2.84−6.62
PFTriA	7.80 ± 3.35	7.93	1.81−13.9	33.5 ± 6.45	33.8	22.5−50.8	23.0 ± 5.65	22.3	14.7−35.2
PFTeA	1.44 ± 0.60	1.53	0.471−2.63	6.74 ± 1.55	7.07	4.36−10.1	4.60 ± 1.38	4.71	2.72−7.00
∑PFSAs	11.77 ± 5.03	12.5	3.37−18.9	31.9 ± 11.1	28.4	19.5−55.2	23.4 ± 8.48	22.1	12.9−37.8
∑PFCAs	20.73 ± 8.85	21.8	5.09−36.5	70.1 ± 15.4	67.5	48.0−109	51.2 ± 13.3	48.2	33.8−78.4
∑PFASs	32.5 ± 13.5	33.5	8.46−51.9	102 ± 25.9	98.2	68.5−164	74.5 ± 21.4	71.1	46.6−116

perfluorooctanesulfonic acid (linPFOS), perfluorononanesulfonic acid (PFNS), perfluorodecanesulfonic acid (PFDcS), perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDcA), perfluoroundecanoic acid (PFUnA), perfluorododecanoic acid (PFDoA), perfluorotridecanoic acid (PFTriA), perfluorotetradecanoic acid (PFTeA), perfluorohexadecanoic acid (PFHxDA), and methyl perfluorohexane sulphonamide (MeFHxSA). Additionally, PFAS of emerging concern were measured: methylperfluorooctane sulfonamide (MeFOSA), ethylperfluorooctane sulphonamide (EtFOSA), perfluorooctanesulfonamidoacetic acid (FOSAA), methyl perfluorooctane sulfonamidoacetic acid (MeFOSAA), ethyl perfluorooctane sulfonamidoacetic acid (EtFOSAA), 4:2 fluorotelomer sulfonic acid (4:2 FTS), 6:2 fluorotelomer sulfonic acid (6:2 FTS), 8:2 fluorotelomer sulfonic acid (8:2 FTS), 10:2 fluorotelomer sulfonic acid (10:2 FTS), 3:3 fluorotelomer carboxylic acid (3:3 FTCA), 5:3 fluorotelomer carboxylic acid (5:3 FTCA), 7:3 fluorotelomer carboxylic acid (7:3 FTCA), a mixture of 6:2 and 8:2 chlorinated polyfluorinated ether sulfonate (F-53B), dodecafluoro-3H-4,8-dioxanonanoate (ADONA), and hexafluoropropylene oxide dimer acid (Gen-X), see SI Table S1. All concentrations are expressed in ng g^{-1} wet weight (ww).

Quality Control. To guarantee the quality and control for reproducibility and precision of the PFAS analyses method, one blank and a standard reference material (human serum AM-S−Y-1908 INSPQ within the Arctic Monitoring and Assessment Program ring test) were concurrently analyzed every 15 samples. The determined concentrations varied between 78 and 125% of the target value. The recovery of the ^{13}C labeled internal standard was calculated by adding a recovery standard at the end of the sample processing to every sample. The recoveries of all internal standard compounds varied between 66 and 120%. Limit of detection (LOD) was defined as three times the signal-to-noise ratio for the specific matrix, or in the case of detection in the blanks as the sum of the average of the blank level and 3 times standard deviation. LOD varied depending on the compounds and ranged from 0.004 to 0.500 ng g^{-1} for the PFAS.

Statistical Analyses. Among PFAS, only compounds detected in >70% of both prelaying females plasma and eggs yolk were included in analyses to increase statistics robustness. For each included PFAS, values < LOD were set to half of the LOD of the specific compound.

First, we tested for each PFAS the relationship between concentrations in eggs and the following biological variables: the laying date, the egg mass and the rank of the egg in the clutch by laying order (egg number: 1 or 2) as well as both interactions between the laying date or the egg mass and the egg number, using linear mixed effect models (LMMs: lme function from "nlme" R-package, v.3.1.147).[56] The females body condition (residuals of the linear correlation between the skull length and the mass) was not included as an explanatory variable in the model as it was correlated to the laying date (LM: $t = -4.054$, $p < 0.001$).

Second, LMMs were built to test the maternal transfer efficiency of each individual PFCAs. The maternal transfer ratio, calculated as *concentration in egg/concentration in female* for each compound, was used as the response variable and log-transformed to meet the assumptions of linear models. The number of carbons in the PFCAs chain, the egg number as well as the interaction between these two variables were used as predictors. For these models, all PFAS concentrations lower than LOD were removed from the data set to avoid outliers in ratios (n = 15).

Third, we investigated for each PFAS the effect of the concentration in females plasma and the egg number on the concentration in eggs using LMMs.

Each model of the three steps were then ranked and rescaled according to the Akaïke's Information Criterion for small sample size (AICc): in a set of models from the full to the null model, the model with the lowest AICc was selected for all steps independently. If the ΔAICc with the next ranked model was <2, the most parsimonious was chosen.[57,58] The nest number was used as a random intercept in all models. The normality of residuals was verified through inspection of diagnosis plots (residuals vs fitted values and Q-Q plots). For all models a significance level of $\alpha < 0.05$ was used. All statistical analyses were performed using R (v.4.0.0; R Core Team, 2020).[59]

RESULTS AND DISCUSSION

PFAS Concentrations in Females and Their Eggs. In the studied population, kittiwakes arrived in the colony in early April after migrating from pelagic areas of the western North

https://doi.org/10.1021/acs.est.1c03773
Environ. Sci. Technol. 2022, 56, 6091−6102

Atlantic Ocean.[60] During the two-months prelaying period that follows migration, females feed mostly on small fish and crustaceans in the marine system near the colony before laying a clutch of usually two eggs.[61−63] Only three nests were observed to have single egg clutches in the present study. Females having a single egg clutch and females having a two eggs clutch had PFAS concentrations of similar magnitude in plasma (respectively, 8.46−35.4 and 12.4−89.4 ng g^{-1} ww). Therefore, they were both considered the same way in analyses.

The following legacy PFAS were detected in >70% of both females plasma and eggs yolk and therefore included in analyses: PFHxS, brPFOS, linPFOS, PFOA, PFNA, PFDcA, PFUnA, PFDoA, PFTriA, PFTeA (SI Table S1). Among legacy compounds, both PFDcS and PFHxDA were above LOD in 84% of the eggs. However, in maternal plasma PFDcS and PFHxDA were above LOD in only 24% and 0% of the samples, respectively. All other legacy PFAS were not detected in maternal plasma nor in eggs. None of the emerging PFAS were detected in the maternal plasma. In contrast, 7:3 FTCA was detected in 84% of the eggs whereas ADONA was only detected in a single egg (SI Table S1). None of the other emerging PFAS investigated were detected in the yolk. PFDcS found in <70% of the females and PFHxDA, 7:3 FTCA and ADONA found in none of the females were therefore excluded from statistical analyses, but descriptive statistics of the compounds in eggs are provided in SI Table S2.

The most abundant PFAS found in maternal plasma were linPFOS (mean ± SD: 10.8 ± 4.70 ng g^{-1} ww), followed by PFTriA (7.80 ± 3.35 ng g^{-1} ww) and PFUnA (6.88 ± 3.22 ng g^{-1} ww, Table 1). Together, these three PFAS represented 78.6% of the $\sum_{PFAS}$. In both eggs, PFTriA was dominant (28.9 ± 7.99 ng g^{-1} ww), followed by linPFOS (25.4 ± 9.89 ng g^{-1} ww) and PFUnA (16.2 ± 5.54 ng g^{-1} ww), representing 78.4% of the $\sum_{PFAS}$. For example, incubating glaucous gulls (*Larus hyperboreus*) sampled in the same area showed dominating linPFOS, then PFUnA and PFTriA in both plasma and eggs.[38,64] Odd-chain PFCAs (e.g., C_9, C_{11}, C_{13}) being more abundant than even-numbered chain is a frequent pattern in seabirds and their eggs, this is believed to be linked to the degradation process of precursor compounds such as fluorotelomer alcohols (FTOH), as well as a selective bioaccumulation.[21,27,44,65−67]

PFCAs in plasma reflect recent dietary uptake due to their efficient elimination from birds' bodies.[68] In contrast, PFOS and other PFSAs show much longer half-lives in plasma, suggesting that blood acts as a significant reservoir for them. Thus, occurrence of PFCAs may represent more recent and local inputs (marine foraging area close to Svalbard), whereas PFSAs would rather represent contamination before birds enter the Svalbard areas to breed (winter and early spring in the West Atlantic).[69] Moreover, plasma samples may represent a snapshot of recent exposure to PFAS while egg concentrations integrate a longer period of time of egg formation, rather reflecting recent days and weeks.[23] In some cases even revealing the exposure at the wintering grounds, hampering direct comparisons of PFAS patterns in plasma and eggs. Kittiwakes in Svalbard nonetheless arrive on the breeding grounds by mid-April and females of the present study were caught on the fourth of June ±8 days (mean ± SD).[60] Before they laid, they were thus feeding locally for a longer time than the length of most PFAS clearance time measured in eggs of PFAS fed hens (*Gallus gallus*).[23,70] Despite different metabolisms and egg-laying pattern (and thus excretion) between these two species, PFAS concentrations of kittiwakes plasma and egg yolks could therefore mainly represent local contamination.

Emerging PFAS in Females and Their Eggs. A broad number of shorter-chain alternatives, supposedly less bioaccumulative and toxic than long-chain persistent PFAS, have been synthesized since the 2000s when C_8 and related PFAS were phased out or regulated in North America and in Europe.[71,72] Even so, some of them have been found in biota, sometimes with higher levels of bioaccumulation and toxicity than the long-chain PFAS they replaced.[45,48,73−79] In the present study, we measured 7:3 FTCA above LOD in 84% of the eggs (mean ± SD: 0.21 ± 0.09 ng g^{-1} ww; range: 0.10−0.40 ng g^{-1} ww). To the best of our knowledge, this is the first report of this compound in seabird eggs, and the second for Arctic top predators.[46] 7:3 FTCA is an intermediate environmental degradation product from fluorotelomer alcohols (FTOH), whose final degradation products are PFCAs.[80] It has been recently detected in human tissues and wildlife.[46,81−87] In eggs of osprey (*Pandion haliaetus*), tawny owl (*Strix aluco*), and common kestrel (*Falco tinnunculus*), this compound ranged from <0.24 (LOD) to 2.7 ng g^{-1} much higher concentrations than those found in kittiwake eggs reported here.[78] Literature regarding fluorotelomer toxicity is scarce and even nonexistent for avian species, but some were found to be potentially more toxic than long-chain PFAS.[88−90] Among emerging PFAS, ADONA was detected in a single egg at a concentration of 0.11 ng g^{-1} ww, which is the first documented finding for this compound in wildlife (chromatograms for ADONA measurements are provided in SI Figure S1). To the best of our knowledge, this compound was detected only twice before in biota, in blood of humans living close to a production plant using ADONA in Germany and in human milk from women in China.[91,92] Therefore we recommend additional investigations for this compound in bird eggs. Other fluorinated alternatives such as F-53B and Gen-X were not detected in any of the samples, F-53B was very recently discovered in herring gull eggs from Germany (despite not being officially used in Europe) and, along with Gen-X, in 100% of black-tailed gull (*Larus crassirostris*) eggs from South Korea with an increasing trend over time.[50,51] None of the analyzed emerging PFAS were found in females plasma in the present study, which means that kittiwakes foraging grounds are not important sources. However, PFAS accumulation in a specific tissue dependent on their physicochemical characteristics.[21] Thus, although we detected 7:3 FTCA and ADONA in eggs yolk and not in maternal plasma, these compounds may be present in other organs of the birds. Another hypothesis for the presence of emerging PFAS in yolk but not in females' plasma could be a very high transfer efficiency of these compounds since some emerging PFAS (including ADONA) have been found to bind to human and rats liver proteins at least as strongly as PFOA or PFOS.[93] A significant transfer of precursors such as FTOH in eggs could also be a reason for the detection of 7:3 FTCA in eggs but not in females, however this is highly speculative as these compounds were not measured in the present study. Adults blood plasma is frequently used in birds to describe the extent of local contamination to a wide range of pollutants.[94] However, in our study this tissue shows its limitation as a tool to document the contamination of the environment, as all emerging compounds investigated and detected in egg yolks could not be detected in any of the

https://doi.org/10.1021/acs.est.1c03773
Environ. Sci. Technol. 2022, 56, 6091−6102

plasma samples. For future studies, we suggest systematic screening for emerging PFAS in biota to increase the overview of the exposure to these compounds and we suggest that the use of eggs would be more pertinent rather than adults plasma. Toxicological studies are also strongly needed to evaluate the threats of the alternative fluorinated compounds in biota.

Relationship between Biological Factors and PFAS Concentrations in Eggs. The variables "laying date" and "egg mass" were excluded from all best models explaining PFAS variations in eggs (SI Table S3). Therefore, developing embryos from eggs laid early or late in the season should have a similar exposure to PFAS. Moreover, juvenile survival is known to be affected by egg size (and therefore egg mass) in various avian species;[95] however, egg mass was unrelated to PFAS contamination in our study. Relationship between laying date and PFAS concentrations in eggs is not commonly studied, but in great tits (*Parus major*) a negative and linear correlation was found between PFOS concentration of eggs and the laying date but no relationship with any of the other PFAS was found.[96] In the present study, the absence of relationship between the laying date and any of the PFAS concentrations in eggs might be due to the highly synchronized and time-limited laying period during which significant variations of PFAS concentrations in Svalbard water would be unlikely. In the same study on great tits, a positive and linear relationship was also noted between PFOS concentration and the egg mass, which was presumably attributed to the lipoprotein content of the eggs, heavier eggs having a higher lipoprotein content, yet the result of the present study do not support this hypothesis. All selected PFAS, but PFHxS and PFOA (null model selected), were in higher concentration in first- than in second-laid eggs (all $t < -2.57$, all $p < 0.03$; Figure 2; SI Table S3). This difference in PFAS concentrations between eggs of the same clutch is generally observed in gulls, but it is not always the case in other birds with larger clutches.[29,52,96] As a consequence, toxicological impairments on hatchability and survival would be more frequent for the first-laid egg, which could be critical for small clutch size species, including kittiwake. Decreasing body contaminant burden along the laying sequence is the main hypothesis to explain the decreasing concentrations in eggs. In species with larger clutch sizes, daily exogenous intakes or food shortage during laying could be of higher importance, leading to variations in blood circulating PFAS and thus in eggs along the laying sequence. In kittiwakes, the similar concentrations observed in both eggs for PFHxS and PFOA might be the consequence of low concentrations of these two compounds in maternal plasma, resulting in a lower transfer efficiency to eggs.

PFAS Transfer Ratios between Females and Their Eggs. Maternal transfer ratios (MTRs) were all higher than 0, which means that eggs are an important excretion route for all measured PFAS compounds in kittiwakes (see Figure 1). The model selection showed that both the length of the PFAS carbon chain, the egg number and their interaction were significant predictors of the MTRs for PFCAs (SI Table S4). MTRs were increasing with the carbon chain length both for first- and second-laid eggs ($t = 12.5$, $p < 0.001$ and $t = 6.87$, $p < 0.001$ respectively; see Figure 1). This suggests a preferential transfer of PFCAs with the longest chains. Similar findings that those of the present study were documented for PFCAs maternal transfer measured between females liver and eggs yolk in herring (*Larus argentatus*) and common guillemots (*Uria aalge*) respectively from North America and the Baltic Sea.[21,27] This pattern may originate from a selective binding of the longest chain length PFCAs to proteins and a subsequent facilitated transfer to the egg. Such a selective binding have been revealed in in vitro studies with a variable affinity of PFAS to bovine serum albumin depending on the carbon-chain length.[97] Moreover, long-chain PFAS generally have greater bioaccumulation potential than short-chain homologues, they are thus more likely to be transferred to the eggs.[6] However, MTRs of PFCAs had no clear trends with the compounds chain length in herring gulls of southern Norway.[19] A linear relationship between MTRs and PFCAs chain length depict the absence of compounds-specific transfer mechanisms. However, a leveling off of the curve on the extremes (see Figure 1) could be the sign of additional transfer mechanisms for PFOA (C_8) and a transfer kinetic barrier for PFTeA (C_{14}).

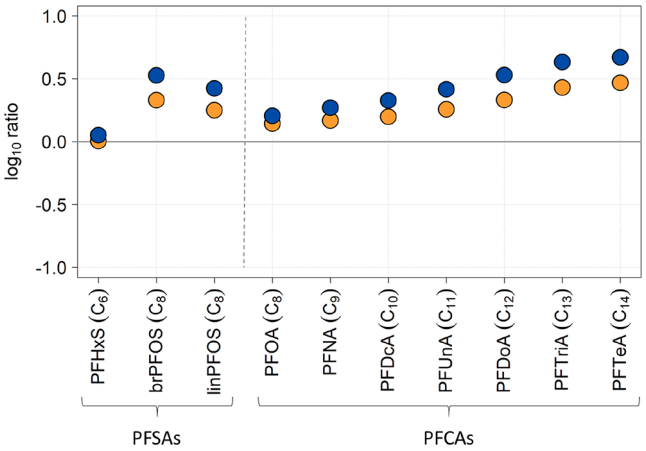


Figure 1. Maternal transfer ratios (log_{10} ratios) of PFAS in black-legged kittiwakes from Svalbard. The PFSAs and PFCAs are ordered by carbon chain length (given in parentheses). Ratios are calculated as log_{10} (mean concentration in eggs/mean concentration in plasma) for first- and second-laid eggs. Blue and orange colors are used for first- and second-laid eggs respectively. The gray horizontal solid line (log_{10} ratio = 0) stand for a 1:1 relationship between female and eggs.

The extent of the MTRs increase with chain length was different between first- and second-laid eggs ($t = -3.25$, $p < 0.01$; see Figure 1), leading to an increasing difference in the MTRs with PFCAs carbon chain length between both eggs. Consequently, second-laid eggs received a lower proportion of females plasma contaminants than first-laid eggs for the compounds with the longest chains. Such a difference could be a consequence of the preferential transfer of the longest chain PFCAs, an increasing transfer of PFCAs with the chain length would lead to a higher depletion of these compounds in females and therefore a lower transfer in their second-laid eggs.

Facilitated transfer of PFCAs with the longest carbon chains is concerning as it could potentially induce adverse effects for the development of the embryo, as toxicity is known to be dependent on the carbon chain length.[41,98,99] However, the majority of the studies on the effects of PFAS exposure on the embryo focused on PFOS and PFOA. These studies revealed that PFOS and PFOA can impair hatchability and disrupt embryos' physiology, but at higher concentrations than those measured in the present study.[31,32,34−36,100−102] Studies on the consequences of long-chain PFCAs in ovo exposure on birds' embryo are needed, especially as long chain PFCAs are widely detected in wildlife, despite decreasing concentrations in the past few years.[65,103−107]

https://doi.org/10.1021/acs.est.1c03773
Environ. Sci. Technol. 2022, 56, 6091−6102

Among PFSAs, PFHxS MTR was lower than those of brPFOS and linPFOS (LMM: $t = -10.4$, $p < 0.001$ and $t = -8.56$, $p < 0.001$, respectively), suggesting, as for PFCAs, an increasing transfer with carbon chain length. PFOS and C_{11}–C_{14} PFCAs have also been found to be more lipophilic than other short-chain PFAS, representing a large proportion of the $\sum_{PFAS}$ in the fat of marine mammals.[108] Seabirds egg yolk being constituted of 20–30% lipids,[109] the maternal transfer of PFAS could be both lipid- and protein-driven. Concerning PFOS, brPFOS was significantly more transferred to the eggs than linPFOS (LMM: $t = -2.50$, $p = 0.02$) despite a similar carbon chain length for these isomers. This may be a consequence of different transfer mechanisms for the branched and linear forms. However, contrarily to linPFOS, brPFOS is a mixture of different isomers and not all of them are covered by the labeled standards used for analyses, potentially leading to lower analytical precision in the measurements of brPFOS concentrations.

PFAS are bound to proteins (including serum albumin, fatty acid binding proteins and organic anion transporters), which affects their distribution, bioaccumulation and excretion.[110] In marine mammals, the trophic magnification factors of individual PFAS were found to have a significant relationship with their protein–water partition coefficients ($\log K_{PW}$).[111] Therefore, PFASs transfer is affected by their binding affinity to proteins. In hooded seals (*Cystophora cristata*) and humans, the transfer efficiency of PFCAs presented a U-shape with a decreasing transfer proficiency from C_8 to C_{10} and an increasing from C_{10} to C_{13} and that of PFSAs was decreasing with compounds chain length.[112−114] The relationship between MTRs and PFASs chain length described in the present study is different. However, this U-shape trend in mammals has been described as the integrated result of opposite trends in the transfer from maternal blood to placenta and from placenta to cord blood.[113] Similar trends than those of the present study were found in the transfer of PFSAs and PFCAs from maternal blood to placenta, this has been described as the consequence of a high water content in blood and a higher protein and lipid content in the placenta. As a consequence, short chain PFASs with greater water solubility and less capacity to bind with proteins were less transferred to placenta. Similar transfer mechanisms between females blood and eggs yolk could lead to the MTRs pattern observed in kittiwakes.

Investigating lipid and protein content of female plasma and egg yolk in future studies would help in understanding the mechanisms behind maternal transfer of PFAS. Sampling females before and after egg-laying as well as males, would also be interesting in order to evaluate if females are depleted in the longest chain PFCAs after laying and compared to males.

Relationship between PFAS Concentrations in Females and Their Eggs. In this study, eggs laid by the sampled females were collected, enabling the study of the actual profile of the maternal transfer of PFAS. Among PFAS, a positive and linear association between yolks and female plasma was observed for the following compounds: PFHxS, brPFOS, linPFOS, PFNA, PFDcA, PFUnA, PFTriA, and PFTeA (all $t > 2.42$, all $p < 0.032$, SI Table S5, Table 2, and Figure 2). A similar linear relationship between females and eggs was documented in tree swallows (*Tachycineta bicolor*) for PFOS, in great tits for PFOS and PFOA, as well as for PFHxS, PFOS, and PFOA in hens.[20,23,32] PFAS have been found to have relatively strong binding abilities to yolk proteins (low-density lipoprotein, high-density lipoprotein and vitellin proteins).[115] All yolk proteins (except immunoglobulins) being synthesized in the liver, it makes it the entry point for PFAS in egg yolks.[116] A linear relationship between females and eggs for most of the PFAS as found in the present study suggests that the efficiency of PFAS transfer mechanisms are not dependent on the concentration in females' plasma. These linear relationships observed between females' plasma and eggs yolk therefore cannot explain the differences found in the PFAS patterns presented above. The affinity of the different PFAS for proteins varies to a large extent, suggesting binding site–specific interactions and facilitated transport of some compounds.

However, PFAS are not always linearly transferred as found between females and eggs for PFHxA in hens and PFCAs (except PFOA) in great tits.[20,23] A comparable absence of relationship was found for PFOA and PFDoA in the present study. At low levels, the transfer dynamic of contaminants could be different. This could have been the case for PFOA, for which we found the lowest concentrations in both the females and the eggs. However, this was not the case for PFHxS which was also in very low concentrations in both females and eggs. Additional studies are needed to reveal whether the nonlinear transfer of PFOA and PFDoA stems from real biological mechanisms or is due to low statistical resolution caused by the low sample size. The linear relationship between both eggs and females for most PFAS validates the use of eggs to assess the female's exposure in kittiwakes, however, we emphasized the relative importance of sampling eggs of similar laying numbers

Table 2. Factors Affecting Each PFAS Concentrations in Black-Legged Kittiwakes' Eggs from Svalbard, Estimated by Mixed Linear Regression Models. Significant *p*-Values Are Bolded

parameter	estimate	SE	*t*-value	*p*-value
PFHxS (R^2m: 0.52; R^2C: 0.72)				
female plasma	0.94	0.22	4.35	**<0.001**
brPFOS (R^2m: 0.59; R^2C: 0.84)				
female plasma	1.25	0.36	3.51	**<0.01**
egg number (2)	−1.18	0.18	−6.68	**<0.001**
linPFOS (R^2m: 0.55; R^2C: 0.93)				
female plasma	1.45	0.39	3.74	**<0.01**
egg number (2)	−9.52	1.14	−8.34	**<0.001**
PFOA (Null Model)				
PFNA (R^2m: 0.48; R^2C: 0.88)				
female plasma	1.10	0.30	3.64	**<0.01**
egg number (2)	−0.38	0.14	−2.68	**0.023**
PFDcA (R^2m: 0.54; R^2C: 0.93)				
female plasma	1.43	0.35	4.13	**<0.01**
egg number (2)	−0.93	0.19	−5.02	**<0.001**
PFUnA (R^2m: 0.38; R^2C: 0.95)				
female plasma	0.96	0.39	2.42	**0.032**
egg number (2)	−5.29	0.54	−9.86	**<0.001**
PFDoA (R^2m: 0.34; R^2C: 0.90)				
egg number (2)	−1.92	0.23	−8.52	**<0.001**
PFTriA (R^2m: 0.61; R^2C: 0.79)				
female plasma	1.09	0.37	2.98	**0.012**
egg number (2)	−1.10	1.50	−7.36	**<0.001**
PFTeA (R^2m: 0.53; R^2C: 0.79)				
female plasma	1.34	0.52	2.59	**0.024**
egg number (2)	−2.21	0.34	−6.60	**<0.001**

https://doi.org/10.1021/acs.est.1c03773
Environ. Sci. Technol. 2022, 56, 6091−6102

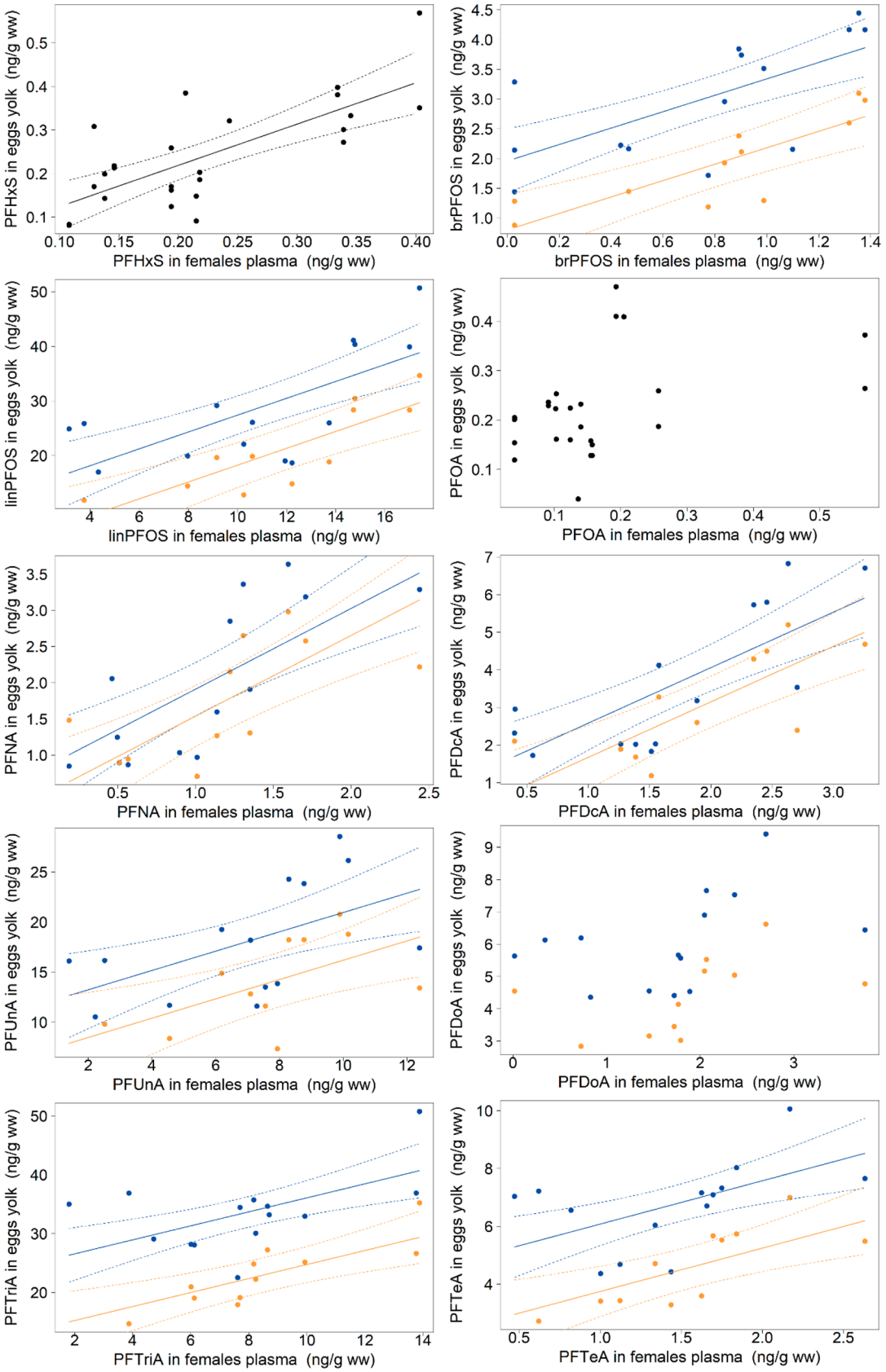


Figure 2. PFAS concentrations (ng g^{-1} ww) relationship between females plasma and yolks of first- and second-laid eggs of black-legged kittiwakes from Svalbard. The solid line refers to a statistically significant linear maternal transfer (see Table 2), with dotted lines representing 95% confidence intervals and no line representing no significant relationship. Blue and orange colors are used for first- and second-laid eggs respectively when concentrations are significantly different between them, black is used if the trends are similar between egg numbers.

https://doi.org/10.1021/acs.est.1c03773
Environ. Sci. Technol. 2022, 56, 6091−6102

to avoid biased estimation due to the decrease in contamination with the laying-sequence.

To conclude, there was no measurable effects of the maternal plasma concentrations of PFAS on the efficiency of the transfer mechanisms into the yolk. However, the physicochemical characteristics of the different compounds (carbon chain length in particular) seem to affect the transfer, with a likely facilitated transportation of the longest chain PFCAs into the yolk. Effects of these long chain compounds on the development of seabird embryos are thus crucial to investigate as development represents a critical period to contaminants exposure. As highly contaminated females lay highly contaminated eggs, kittiwake embryos might be at strong risk as they are impacted twice by the female exposure to contaminants: (1) via impaired incubation and chick-rearing behaviors and (2) via maternal transfer to the egg with impaired embryonic and early days physiology and development. Therefore, for further studies, estimating the outcomes of the maternal transfer of PFAS on avian development physiology is essential to assess if this leads nestlings to a bad start in life, especially for emerging fluorinated compounds which are under-represented in experimental studies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c03773.

Internal standards used in PFAS analyses; List of targeted PFAS; descriptive statistics in eggs for PFDcS, PFHxDA, and 7:3 FTCA; chromatograms of the measurement of ADONA in one egg; model selection for the relationship between PFAS and biological variables in eggs; model selection for maternal transfer ratios; model selections for the maternal transfer of PFAS in eggs (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This project was supported by IPEV (prog. 330 to O. Chastel), the ANR ILETOP (ANR-16-CE34-0005). W. Jouanneau was funded by a PhD grant from the University of La Rochelle, France. D.-J. Léandri-Breton was funded by the Natural Sciences and Engineering Research Council of Canada, the Fonds de Recherche du Québec − Nature et Technologies and the Northern Scientific Training Program. We express our gratitude to French Polar Institute (IPEV) and the Alfred Weneger Institute (AWI) wintering staff in Ny-Ålesund as well as the Norwegian Polar Institute (NPI) for their help and logistic support during the field season. We also thank Linda Hanssen for her help in analyzing PFAS. This article benefited greatly from the comments of three anonymous referees.

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