



Plastics in stomachs of northern fulmars *Fulmarus glacialis* collected at sea off east Greenland: latitude, age, sex and season

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Abstract

A sample of 145 stomachs from fulmars hunted 100 km offshore east Greenland 64° 30' N in early June 2015 was analysed for abundance of plastic litter. Overall, 86% of the stomachs contained plastics with an average of 13.5 particles, and 0.14 g per stomach. A proportion of 42% of the stomachs exceeded the level of 0.1 g plastic, whereas the international policy target aims at a reduction to less than 10%. The observed quantity of ingested plastic fits a pattern of reduced plastic abundance at higher latitudes, at greater distance from densely populated and industrialised areas. A subsample of 20 fulmars of known age and sex indicated that young birds contained more plastic than adults, and females more than males. Indirect evidence from age and sex composition in the full sample supported these findings. Further confirmation was found in literature and by re-analysis of earlier datasets. Differences in colony attendance could explain the combined effects of age, sex, and possibly season on plastic abundance in the stomachs. With a consistent monitoring sampling regime, such variations do not impair the results, but for evaluation of regional patterns from incidental observations or the planning of new monitoring schemes they are important.

Keywords *Fulmarus glacialis* · Plastic ingestion · Regional pattern · Sample composition · Latitude · Age · Sex · Season · Colony attendance

Introduction

Comparable regional and temporal assessments of marine plastic pollution are important to identify the sources, distributional pathways and ultimate accumulation of plastics in the global marine environment. Such data can support appropriate responses through governmental policies and increased stakeholder and public awareness. The abundance of plastic in stomach contents of a seabird, the northern fulmar *Fulmarus glacialis* (from here on 'fulmar') has grown into an international monitoring instrument to demonstrate

changes over time and to describe spatial patterns (Van Franeker et al. 2011, 2021; Van Franeker and Law 2015). The approach is firmly embedded in marine policies of the Convention for the Protection of the Marine Environment of the Northeast Atlantic (OSPAR) and the European Union Marine Strategy Framework Directive (EU-MSFD) (OSPAR 2015; EC 2017) and has increasingly entered into wider north Atlantic and Pacific environmental policies (Linnebjerg et al. 2021; Environment Canada 2020). Policy targets for ecological and environmental quality in the North Sea require that the proportion of stomachs containing more than 0.1 g of plastic must be reduced to under 10% of birds investigated.

The 10% limit for the proportion of birds exceeding 0.1 g of plastic in the stomach has been set arbitrarily by OSPAR (2009) as one of its Ecological Quality Objectives (EcoQOs). The European MSFD, however, demands a non-arbitrary data-based approach that aims to set 'Threshold Values' considered to cause 'no harm' to the marine ecosystem (EC 2017). Since 'harm' from marine litter is hard to assess, the MSFD decided that a Threshold Value could be derived from the most pristine

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known environment. Van Franeker et al. (2021) proposed to use the combined High Arctic Canadian samples from Mallory et al. (2006), Mallory (2008), Provencher et al. (2009) and Poon et al. (2017) as the most pristine known situation: in these High Arctic Canadian samples, 18 out of 179 fulmars, or 10.06% exceeded the level of 0.1 g of plastic in the stomach. Since this databased pristine value is almost identical to the long-term OSPAR target, the earlier OSPAR EcoQO can be considered equivalent to the new Fulmar Threshold Value (Fulmar-TV or FTV): both require that the proportion of fulmars with more than 0.1 g plastic in the stomach must be reduced to less than 10%.

In addition to increased monitoring, incidental studies of stomach contents from fulmars contribute to a growing body of baseline data. This paper adds baseline information on plastic ingestion by fulmars collected at sea off east Greenland, a region not surveyed previously. We aim to examine this new sample in the light of earlier studies which suggested that the quantity of plastics in fulmar stomachs tended to decrease with increasing latitude, presumably related to an increase in distance from densely populated and industrialised areas (Kühn and Van Franeker 2012; Trevail et al. 2015).

In this, it is important to accept that baseline reports do not reflect a balanced regional average of plastics ingested by fulmars. Spatial and seasonal spread in sampling, or the lack thereof, variations in regional marine pollution levels, and variables such as the origin, age and sex composition of birds in the sample, might cause variations in the plastic mass recorded in the stomach (Provencher et al. 2017). Reports from a new fulmar monitoring program in northern Iceland suggest substantially higher mass of plastics in the stomachs of females compared to males (Snaethorsson 2018, 2019, 2021). The extensive long-term dataset for the North Sea showed that, in addition to temporal change, a significant difference in relation to age exists in which adult (breeding age) fulmars have less plastics in the stomachs than younger age-classes (Van Franeker and Meijboom 2002; Van Franeker et al. 2011, 2021). The analyses in those studies could not detect an additional significant contribution of male or female gender on ingested plastic mass. However, since our Greenlandic sampling location was not too distant from the study locations in Iceland, we aimed to dedicate special attention not only to the latitudinal pattern, but also to variables like age and sex potentially affecting the measurement of plastics in the stomachs.

Materials and methods

On the 3rd of June 2015, during longline fishing operations by the Faroese fishing vessel Núbber to the east of Greenland, around position 64° 30' N 36° 20' W, fulmars were

hunted for traditional human consumption (Jensen 2012) using a long-handled net (fleyg). The location was in the open oceanic environment, approximately 100 km east of the nearest Greenlandic coast and about 560 km west of Iceland. In total 145 birds were captured, of which 125 were immediately skinned, cleaned and stored frozen. From these birds, heads with oesophagus and stomachs still attached were kept for research of the stomach contents. Twenty carcasses could not be cleaned on the ship, and were frozen whole. These were later necropsied in detail before the body was processed for consumption. Dissections of the whole birds followed the methods described in Van Franeker (2004) and OSPAR (2015). The dissection protocol includes a range of morphometrics, plumage colour and moult, anatomical details related to sex, age, active breeding status, health and body condition. For the head plus stomach samples only head measurements and colourphase could be assessed.

In fulmars, the colour of the plumage is indicative of origin. In the complete carcasses, plumage colour could be recorded using the four colourphase system proposed by Fisher (1952) which was further detailed in Van Franeker and Wattel (1982) and Van Franeker (1995) and is also used in the OSPAR (2015) monitoring program. Following a pattern with increasing portions of the body becoming feathered grey rather than white, the four phases are: Double Light (LL), Light (L), Dark (D) or DD (Double Dark). In the incomplete carcasses this system could not be used, but the alternative classification as 'White' (colourphase LL) opposed to 'Coloured' (L, D, DD) was possible. This distinction used the feather colour on top of the head and upper neck which is white in LL birds but shows variable shades of grey in L, D and DD fulmars. In temperate and subarctic Atlantic fulmar populations (Europe, Iceland, Jan Mayen, south and west Greenland, Newfoundland, Labrador) 99% to 100% of the birds are of the White colourphase (LL). In contrast, coloured individuals are the dominant type with 90% or more in High Arctic populations (Arctic Canada, far NE Greenland, Bear Island, Svalbard) (Van Franeker and Wattel 1982; Van Franeker 1995).

For the head-with-stomach samples, head measurements were used to assign probable sex using the approach of calculating discriminant scores as described in Van Franeker and Ter Braak (1993). The sex discriminant in Van Franeker and Ter Braak (1993) focused on the use of length of head and culmen, depth of bill and length of tarsus to create a generalized discriminant ('GENDIS'). In our current study, tarsus length was missing, but using the same data for fulmarine petrels of known sex as Van Franeker and Ter Braak (1993), we used the GENDIS program to calculate a relevant discriminant formula on the basis of head measurements only. Using the three available head measurements GENDIS calculated the formula as $GEN3 = \text{headlength} + 2.08 * \text{bill-depth} - 0.24 * \text{culmenlength}$. Next, the program UNMIX was

used to estimate the cutpoint in the Greenlandic discriminant scores, that is the best estimated value to separate scores of the larger males from the smaller females. GENDIS and UNMIX PC programs provided in Van Franeker and Ter Braak (1993) no longer work and were rewritten by Cajo ter Braak to operate under modern Windows versions. Also an R-package (R Core Team 2020) for the GENDIS and UNMIX programs has been made available (Ter Braak 2021) and was used after installing it in R by `install.packages("remotes")`; `remotes::install_github("CajoterBraak/Gendis2unmix")`; `library("Gendis2unmix")`. The site also provides our file on sexed fulmarine petrels used to calculate discriminant formulas using different character combinations, plus an example file of unsexed fulmars from a study on Jan Mayen to calculate a cutpoint.

There is no equivalent method to assign age to the birds from which we had only the head and stomach. Indirectly the necropsied birds suggested that in our sample, plumage colour might be used as a rough proxy for age.

Stomach contents were analysed according to the standard methods of the North Sea fulmar monitoring program (as described in the supplement of Van Franeker et al. 2011, 2021; OSPAR 2015). Contents were rinsed with cold water over a 1 mm mesh sieve and sorted under binocular microscope into categories of marine litter, normal food, and natural non-food items. Plastics and other anthropogenic litter items were split into different subcategories, which were then counted and weighed on an electronic weighing scale in grams accurate to the 4th decimal. Subcategories that weighed less than 0.0000 g were considered to weigh 0.0001 g. Averages are given as population averages with standard errors (\pm se), meaning that birds with no plastics were included in the calculation.

Data from dissections and stomach content analysis were initially recorded in Excel spreadsheets and then stored in Oracle relational database. Mass data for plastics in fulmar stomachs were not normally distributed. Thus, in order to test for differences in ingested quantities of plastic between sexes or age groups, we used the non-parametric Mann–Whitney *U* test (Genstat 19th edition; VSN International 2017).

In principle, OSPAR (2020) has announced to follow the Threshold Value approach and terminology as proposed by Van Franeker et al. (2021), but this has not yet been implemented in the MSFD. For the time being, in this paper, we, therefore, use the existing EcoQ terminology. The proportion of birds in a sample exceeding the 0.1 g level of plastic in the stomach is expressed as EcoQ Performance or EcoQ% (in the new terminology FTV-Performance or FTV%). As proposed by Van Franeker et al. (2021), in the Fulmar-TV approach, the difference of samples from the Threshold Value was tested using the 2-sample *z*-test by Sergeant (2019) as provided at <http://epitools.ausvet.com.au/content.php?page=z-test-2>.

When using this test, the Fulmar-TV terminology is used. Lack of statistical difference means that the observed value is close to the targeted EcoQO, not that the actual 10% value has been reached.

Presence of a latitudinal trend in EcoQ% was tested using a GLM approach (Genstat Generalized Linear Modelling; VSN International 2017), more specifically in a logistic analysis dedicated for binomial distributions (number of birds in the sample and number of birds above the EcoQO and using logit transformation. Relative contributions from different variables like year, age or sex to the yes or no compliance of individual birds with the EcoQO, were evaluated in a GLMM approach for binomial distribution with Wald tests (Genstat, Generalized linear mixed model analysis, VSN International 2017). Statistical significance was set at level $p < 0.05$ in all tests.

A thorough literature search was conducted to find all studies that presented data on ingested plastic mass by fulmars in the north Atlantic and Pacific Oceans. Due to our long track record of study of plastic ingestion by fulmars since Van Franeker (1985), most literature was known to us and was used in Kühn and Van Franeker (2020). In more recent years, this was complemented by continuous use of search engines such as Google Scholar and Web of Science or alerts by ResearchGate and common journals for plastic research (search terms: ‘species name’ and plastic, litter, debris, ingest, entangle, diet). Citations in each plastic ingestion study were checked for additional references.

Results

Necropsy findings from the 20 complete carcasses revealed 14 females and 6 males, all in fine body condition (average condition index 8.2 on scale 0–9). In age composition, 13 from the 20 birds were adults. Among the 13 adults 11 were considered to be actively breeding in the 2015 season and two were likely at breeding age but seemed to have either failed early or were not breeding this year. Among the seven non-adults, there were four immatures, two second-year birds (3rd calendar-year) and one first-year juvenile (2nd calendar-year). Fifteen of the 20 birds (75%) were of the double light (LL or White) colourphase, the other 5 were ‘Coloured’ in colourphases L and D. All five coloured individuals were non-adults that lacked a bare incubation patch and were not close to breeding age. In sharp contrast, all fifteen LL birds had a well-developed incubation patch, including two adults that were considered not actively breeding and the two birds classified as immatures (in which the incubation patch was at least partly present, thus indicating subadult age). Among the 15 LL birds, the reproductive organs showed that 11 (73%) were actively breeding at the time of collection, suggesting relatively nearby nesting. For

Table 1 Plastic presence in stomachs of 145 fulmars by age and sex caught off east Greenland in June 2015, expressed as average number of plastic particles ($n \pm se$) and average plastic mass ($g \pm se$) per bird including maximum values, the proportion of birds with plastic in the stomach (Frequency of Occurrence %FO), and the proportion of birds having more than 0.1 g of plastic in the stomach (EcoQ%)

	Sample size	Number of plastic particles		Mass of plastic particles			
		Number $\pm se$	Max nr	gram $\pm se$	Max g	%FO	EcoQ%
ALL	145	13.5 \pm 1.8	151	0.14 \pm 0.02	1.15	86%	42%
Aged by dissection							
Non-adult	7	34.6 \pm 11.8	96	0.28 \pm 0.15	1.15	100%	57%
Adult	13	14.8 \pm 4.6	48	0.20 \pm 0.07	0.08	92%	46%
Aged by proxy colouration							
'Non-adult' (C)	12	39.5 \pm 13.0	151	0.27 \pm 0.11	1.15	92%	42%
'Adult' (LL)	133	11.1 \pm 1.4	86	0.13 \pm 0.01	0.76	85%	42%
Sexed by dissection							
Female	14	27.0 \pm 6.9	96	0.30 \pm 0.09	1.15	93%	64%
Male	6	9.3 \pm 5.9	37	0.07 \pm 0.04	0.27	100%	17%
Sexed by discriminant function							
Female	73	17.6 \pm 3.0	151	0.16 \pm 0.03	1.15	93%	51%
Male	72	9.3 \pm 1.8	86	0.12 \pm 0.02	0.66	78%	33%

individual details, see the Electronic Supplementary Material, ESM Tables I and II.

Sex-discriminant scores for all birds were calculated using the GEN3 formula with head measurements (see methods). The UNMIX program calculated the GEN3 cutpoint value to split the females from males in our sample at score 120.8085. This cutpoint assigned the correct sex to all 20 individuals sexed by dissection indicating good reliability of the method. However, larger samples of sexed birds are needed for a more exact measure of reliability, still, tests in Van Franeker and Ter Braak (1993) suggest reliability for northern fulmars to be at least 95%. In the total sample of 145 birds, the discriminant score assigned female sex to 73 birds and male sex to 72 birds. Details on the discriminant scores and assigned sex of all individual birds, along with a histogram of the GEN3 scores have been provided in ESM Table II and ESM Fig. 1.

Plastics were present in 125 of 145 stomachs (%FO 86%). Calculated over the full sample of 145 birds, the average number of plastics with standard error was 13.5 ± 1.78 particles per stomach, with an average mass of 0.14 ± 0.016 g. A proportion of 42% of the 145 birds exceeded the level of 0.1 g plastic in the stomach (EcoQ% 42%), significantly above the Fulmar-TV ($z = 6.7$, $p < 0.0001$). Industrial plastic pellets represented about 15% of the plastic mass. Hard plastics, that is the industrial pellets plus user fragments dominated plastic mass by 90% of the total mass. Non-plastic litter was relatively rare and represented about 11% of the combined mass of plastic and non-plastic litter. Full details of presence of different categories and subcategories of plastics and other anthropogenic litter in the stomachs are given in ESM Table III. Among the 20 dissected birds (Table 1), 7 non-adults averaged at 0.28 ± 0.15 g of plastic in the stomach, more than the 0.20 ± 0.07 g in thirteen adults but not

significantly different by Mann–Whitney U test ($U = 34$, $p = 0.393$). For the complete sample of 145 birds we lack a firm age assessment, but in our opinion, in this specific sample, colourphase may be used as a rough proxy for age, because among the dissected birds all coloured birds were young fulmars whereas all LL birds were older, all adult or subadult. Data in Table 1 indicate that the 133 'likely adult LL' birds contained on average only half the plastic mass found in the twelve 'likely non-adult' coloured individuals. These findings are in accordance with the age results from necropsies, although also in this larger sample the difference was not significant in the Mann–Whitney U test ($U = 582$, $p = 0.122$).

Concerning potential sex-related differentiation in plastic ingestion, we found that among the 20 dissected fulmars, fourteen females averaged at 0.3 ± 0.09 g plastic in the stomach, considerably higher than the 0.07 ± 0.04 g plastic found in six males; yet the difference was not significant according to the Mann–Whitney U test ($U = 20$, $p = 0.076$). When considering sex differences in the full sample split by discriminant scores, 73 birds of assigned female sex on average had 0.16 ± 0.03 g plastic in the stomach, 25% more than 72 assigned males with 0.12 ± 0.02 g (Table 1), a significant difference according to a Mann–Whitney U test ($U = 2068$, $p = 0.027$).

Figure 1 and Fig. 2 show examples of plastics in the stomachs of our Greenlandic birds. There are more photographs in the Electronic Supplementary Material with ESM Table IV providing details of the stomach contents shown.

Results of the literature search for publications that provided quantitative information on plastics in fulmar stomachs in the North Atlantic and North Pacific Oceans are shown in Table 2. Since the purpose of this search was a survey of a potential latitudinal trend in the quantity of



Fig. 1 Stomach content of fulmar GRL-2015-017, a coloured juvenile female that contained the highest plastic mass in our sample of 145 birds. Twenty industrial plastic pellets (left), 4 sheets (centre bottom), 8 threads (centre top) and 64 fragments (right) added up to 1.1505 g of plastic. The scale bar shows mm



Fig. 2 Stomach content of fulmar GRL-2015-002, a double light coloured adult breeding female with plastics just under the 0.1 g used in the target definition of ecological quality or good environmental status. The stomach contained 17 plastic particles weighing 0.0911 g. According to the EcoQO, 10% of stomachs may contain more plastic than in this example; the other 90% may still have plastic in the stomach, but not more than in this example

ingested plastic, we restricted data in Table 2 to more recent studies published after year 2010 that used data from mostly well after the year 2000. Thereby we largely avoid bias from temporal change as shown for previous decades in Van Franeker and Meijboom (2002), Van Franeker et al. (2011), and Van Franeker and Law (2015). Thus, early studies are not included in the table (Bourne 1976; Baltz and Morejohn 1976; Day et al. 1985; Furness 1985; Van Franeker 1985; Moser and Lee 1992; Robards et al. 1995; Blight and Burger 1997; Van Franeker and Meijboom 2002; Van Franeker et al. 2011). Regional coverage in new publications was sufficient to replace the older sources. Not all recent sources provided

details on number and mass of plastic particles, but all provided the main monitoring parameter of the proportion of stomachs in their sample exceeding 0.1 g of plastic.

In the Fulmar-TV approach, the sample from our current study had 145 fulmars of which 42% exceed the 0.1 g limit, which was significantly above the Fulmar-TV ($z=6.7$, $p < 0.0001$). When a sample is significantly above the EcoQO or Fulmar-TV, additional policy action is needed in order to comply with the policy target.

Discussion

Latitudinal pattern

Plastic contents in the stomachs of all 145 fulmars in our Greenland sample averaged 0.140 ± 0.016 g, with 42% of birds exceeding the 0.1 g level. Several studies (Kühn and Van Franeker 2012; Trevail et al. 2015) have suggested that in the north Atlantic, the quantity of plastics in fulmar stomachs tends to decrease with increasing latitude, presumably related to an increase in distance from densely populated and industrialised areas. For comparison, stomachs of 125 fulmars from the Dutch coast found in the 2013–2017 period contained on average 0.259 ± 0.045 g of plastic (Van Franeker and Kühn 2018), thus a factor 1.85 higher than in the Greenland sample in year 2015. Also the proportion of different (sub-)categories of plastics in stomachs illustrated the distance from major sources of litter. Industrial pellets and hard plastic fragments, resistant to fragmentation, represented 90% of the overall mass of plastic in the Greenland sample, but this was 51% in the Dutch sample, the remainder being softer materials like sheets and foams. Similarly, non-plastic degradable litter represented 11% of total litter mass in the Greenland sample, whereas the figure for Dutch birds was 44% (Van Franeker and Kühn 2018). Softer materials like plastic sheets and foams, and paper litter are assumed to travel less far due to disintegration on the ocean surface (Suaria et al. 2020). Thus, both quantity and composition of litter in the Greenland birds illustrated distance from more polluted waters like those in the southern North Sea.

Using currently available published sources (Table 2), a latitudinal decline in ingested plastics is illustrated in Fig. 3: the proportion of fulmars exceeding the level of 0.1 g of plastic in the stomach declines at higher northern latitudes, and this applies to data from both the Atlantic and Pacific Ocean. A GLM logistic regression of the binomial proportions of birds in the samples with over 0.1 g plastic shows a significant negative correlation ($t = -32.32$, $p < 0.001$) with the latitude where birds were collected. In Fig. 3, the open blue circle refers to our east Greenland sample, which fits in with the latitudinal pattern. Considerable variations can be seen in especially the higher latitudes, with data mostly

Table 2 Quantities of plastics recorded in stomachs from fulmars collected at different locations

Location				Plastic number		Plastic mass			
North Atlantic	Year(s)	Lat-lon range	Sample size	%FO	$n \pm se$	$g \pm se$	EcoQ%	Source	
Sable Island	2001–2012	44 °N–59 °W	176	93%	26.4 ± 2.9	1.09 ± 0.15	66%	Bond et al. (2014)	
Ireland	2012–2016	53°N–9 °W	14	93%	65.4 ± 32.7	1.11 ± 0.57	93%	Acampora et al. (2016)	
Labrador Sea	2014–2015	54°N–57 °W	70	79%	11.6 ± 2.6	0.15 ± 0.03	34%	Avery-Gomm et al. (2018)	
North Sea	2014–2018	55°N–5 °E	393	92%	21.4 ± 2.1	0.26 ± 0.03	51%	Van Franeker et al. (2021)	
Faroe Islands	2007–2011	62°N–7 °W	699	91%	11.3 ± 0.6	0.15 ± 0.01	40%	Van Franeker et al. (2013)	
East Greenland	2015	64°N–36 °W	145	86%	13.5 ± 1.8	0.14 ± 0.02	42%	This paper	
West Greenland Coast	2016	± 66 °N–54 °W	31	87%			39%	Strand et al. (2018)	
Iceland	2011	66°N–23 °W	58	79%	6.0 ± 1.0	0.13 ± 0.04	28%	Kühn and Van Franeker (2012)	
Iceland	2013–14	66°N–23 °W	40	90%		0.12 ± 0.02	48%	Trevail et al. (2014)	
Iceland (66°N)	2018–2020	65–67 °N—17 °24 °W	121	67%	4.2 ± 0.8	0.08 ± 0.03	13%	Snaethorsson (2018, 2019, 2021); raw data	
High-Arctic Canada	2018	67° N–62 °W	29	72%	1.7 ± 1.6	0.02 ± 0.03	3%	Baak et al. (2020)	
West Greenland offshore	2016	± 70 °N–60 °W	32	84%			31%	Strand et al. (2018)	
North Norway	2013	71 °N–20 °W	72				35%	Herzke et al. (2016)	
High-Arctic Canada (72 °N) proposed Threshold Value	2002–2013	67–77 °N; 62–68 °W	179	43%	2.5 ± 0.4	0.04 ± 0.01	10%	Van Franeker et al. (2021)	
NE-Greenland (76 °N)	2017	± 74–78 °N–4–20 °W	31	90%	6.2 ± 1.5	0.06 ± 0.02	10%	Ask et al. (2020)	
Svalbard	2013	78 °N–15 °E	40	88%	15.3 ± 5.5	0.08 ± 0.02	23%	Trevail et al. (2015)	
California	1997–2010	37 °N–123 °W	437	94%			89%	Nevins et al. (2011)	
Washington/Oregon	2008–2013	46 °N–123 °W	143	90%	19.5 ± 2.1	0.46 ± 0.07	63%	Terepocki et al (2017)	
British Columbia	2009–2010	49 °N–126 °W	36	97%	52.9 ± 17.2	0.35 ± 0.09	61%	Avery-Gomm et al. (2012)	
Alaska	2005–2009	58 °N–145 °W	? (100?)	63%			25%	Nevins et al. (2011)	

Data limited to the current century. In addition to sampling location, year(s), and geographical position or range, the table provides the number of birds in the sample, the frequency of occurrence of plastics, average number and mass of plastic ± standard errors, the proportion of birds having more than 0.1 g of plastic, and finally the reference for those data. Data in Van Franeker et al. (2021) on the Canadian High Arctic were used to set the EU-MSFD Fulmar Threshold Level. Sample size for Alaska was conservatively estimated at 100 for logistic regression

derived from ad-hoc samples, for example the widely different samples from Iceland. Only three samples shown in Table 2 and Fig. 3 are not significantly different from the Fulmar-TV: a sample from northeast Greenland (Ask et al. 2020; $n = 31$, $z = 0.1$, $p = 0.92$), a recent sample from the Canadian Arctic (Baak et al. 2020; $n = 29$, $z = 1.3$, $p = 0.20$), and the Icelandic sample from the combined data from Snaethorsson (ESM Table V; $z = 0.6$, $p = 0.52$). However, in OSPAR terminology, the EcoQ% of 13% for the Icelandic samples does not meet the OSPAR EcoQO.

An evaluation of Table 2 and Fig. 3 needs to consider the various variables that might affect the observed EcoQ%. The pilot study by Van Franeker and Meijboom (2002) investigated variables that could potentially bias measurements of temporal trends in plastic ingestion, such

as sample size, seasonal variation, sex, age, origin, condition, and cause of death. Van Franeker and Meijboom (2002) found that, in addition to sample sizes, age was the only variable found to potentially affect the temporal trends in the Dutch monitoring results. Because younger birds had more plastics in the stomach than adults, a consistent change in age composition of samples over the years might bias temporal trends in plastic ingestion. Such issues are also highly relevant for the interpretation of incidental studies like our current one and several others in Table 2 and Fig. 3. In the light of new data since Van Franeker and Meijboom (2002) not only sample size and age composition of samples are considered, but also origin, sex composition, and finally season (time of year).

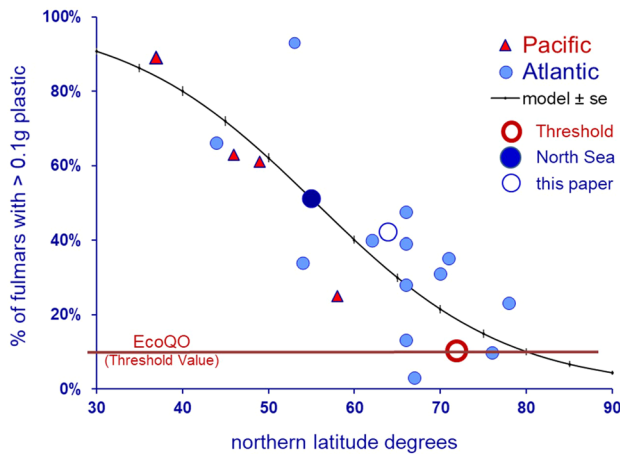


Fig. 3 Logistic model of the percentages of fulmars exceeding the 0.1 g level of plastic in the stomach as reported in different studies, plotted against the latitude of sampling locations. Circles refer to Atlantic studies, the large white-filled circle reflects results of the current study, the enlarged dark circle reflects the North Sea (Van Franeker et al. 2021). Triangles provide information on fulmar studies in the Pacific. The large red circle reflects the combined EcoQ% for High Arctic Canada as used in the assessment of the Fulmar Threshold Value (horizontal red line) (Van Franeker et al. 2021). Full details on sources of plotted data and additional information is provided in Table 2

Sample size

Van Franeker and Meijboom (2002) advised that a reliable average for a specific location and time period required a sample size of 40 birds or above. Note that not all samples in Table 2 and Fig. 3 reach such sample size, including Ask et al. (2020) and Baak et al. (2020), sources mentioned above as samples lacking statistical difference from the Fulmar-TV. The outlying high EcoQ% of 93% for Ireland (Acampora et al. 2016) at the lower latitude of 53°N is based on a sample size of only 14 birds. However, the overall GLM logistic regression incorporates sample size, and the significance of the latitudinal trend is the same with, or without the Irish fulmars.

Origin

Van Franeker and Meijboom (2002) showed that in the North Sea, the origin of birds, as indicated by plumage colour, did not affect the quantity of plastics in the stomach: coloured fulmars in the North Sea in general have plastic loads characteristic for the North Sea, without significant effect of their distant High Arctic origin (Van Franeker and Meijboom 2002). Among beached fulmars in the southern North Sea, the proportion of coloured individuals was about 9% (Van Franeker and Kühn 2020), whereas the nearest colony with coloured fulmars is about 2500 km to the north. Apparently, on average, fulmars stay around in a specific

area long enough to build up plastic contents in the stomach characteristic for that area. However, there is a rare example of a sudden influx of Arctic fulmars into the North Sea, followed by near instant mortality: in that situation bias from origin was demonstrated (Van Franeker and the SNS Fulmar Study Group 2011). As theoretically the same might occur in incidental open ocean samples, the origin of the fulmars in incidental samples away from colonies should be checked when possible.

Fulmars are known to spread widely around the North Atlantic (e.g. Grissot et al. 2020; Dupuis et al. 2021). Distributional maps for fulmars from the UK (Birdlife International 2021) and for fulmars from a range of east Atlantic fulmar colonies (NINA and NPI 2021) show that the birds from these colonies regularly visit distant waters of the Barents Sea and Labrador Sea, and can also disperse to the waters around south and east Greenland. Thus, although for samples taken at sea or on coasts without fulmar colonies, it might seem likely that nearby origins dominate, this cannot be taken for granted. In our Greenland sample 12 of 145 birds (8%) had a coloured plumage. Since the number of coloured individuals in breeding colonies close to our sampling location is very low, part of our coloured birds may have had an origin in the distant but large coloured populations of Bear Island, Svalbard and High Arctic Canada (Van Franeker and Wattel 1982; Van Franeker 1995). The stomach contents of our coloured fulmars had relatively high loads of plastic (Table 2), but this is likely related to age rather than origin (see “Discussion” below).

In principle, also the origin of the double light fulmars in our sample could be diverse. Fulmars are not abundantly breeding in east Greenland. The nearest colony, estimated at 500–1000 pairs of probably LL birds is located at ± 650 km to the south just round the southern tip of Greenland at Kap Christian (Boertmann 2004). A few small colonies exist in the Scoresby Sound area, about 870 km to the north (Boertmann et al. 2020) where the double light colourphase probably also dominates (van Franeker and Wattel 1982). Slightly larger colonies, but with 98% coloured fulmars are known around distant Mallekukfeld in northeastern Greenland (Falk and Møller, 1995) roughly 2000 km to the north. The combined population size of these fulmar colonies in east Greenland, from the southern tip to the far northeast, is estimated at less than 3000 pairs (Boertmann 2004; Boertmann et al. 2020). Such small populations are unlikely to dominate the fulmars at our offshore sampling location. In contrast, an estimated 1.3 million fulmar pairs (Kolbeinsson et al. 2019) of the double light colourphase breed in Iceland with major colonies in the northwest at about 560 km distance from our sampling location. It seems likely that many of the fulmars collected in our study have an Icelandic origin because eleven of fifteen necropsied LL birds in our samples were considered to be actively breeding, which suggests that an

important part of birds sampled in this study must have its origin ‘nearby’, likely in the relatively close and very large colonies located along the west coast of Iceland.

Age

In our current study, non-adult (juvenile to immature) birds had substantially more plastic in the stomach than adults. Although not statistically significant, this difference agrees with earlier findings. The pilot study by Van Franeker and Meijboom (2002) and all later annual Dutch fulmar monitoring reports (last: Van Franeker and Kühn 2020) and international publications (Van Franeker et al. 2011, 2021; Van Franeker and Law 2015) have shown that, in addition to temporal trends (year of collection), age had a substantial impact on the quantity of plastic in fulmar stomachs in which non-adult fulmars consistently had more plastic in the stomach than adults. After the Van Franeker and Meijboom (2002) pilot study, no specific tests were applied in publications, as they focused on temporal trends for all age groups combined. However, in Van Franeker et al. (2021), it was shown that age was a significant covariate in the logistic model of annual proportions of birds exceeding 0.1 g of plastic in the North Sea from 2002 to 2018. Using the raw data underlying Van Franeker et al. (2021), Mann–Whitney U tests over the 2002–2018 period showed that non-adults ($n = 1176$; average plastic mass 0.342 ± 0.0218 g) had significantly more plastic than adults ($n = 1373$; 0.287 ± 0.0218 g) ($U = 695,070$, $p < 0.001$). When restricting the dataset to reduce potential bias from temporal change, the recent 5-year period 2014–2018 showed a similar significant level of higher plastic ingestion by younger birds (223 non-adults with 0.285 ± 0.0340 g) compared to adults ($n = 144$, 0.217 ± 0.0447 g plastic; Mann–Whitney U test $U = 12,788$, $p < 0.001$). A re-analysis of original data for fulmars with known age from the Faroe Islands 2007–2011 from Van Franeker et al. (2013) showed that in 177 non-adults plastic mass averaged at 0.192 ± 0.0167 g of plastic, compared to a lower 0.122 ± 0.0102 g in 375 adults, a statistically significant difference ($U = 24,032$, $p < 0.001$). For the Pacific Fulmar, Avery-Gomm et al (2012) and Terepocki et al. (2017) demonstrated that juveniles had more plastics than older birds. Recently, Shugart and Nania (2021) added to these publications and strongly emphasized that in their study juvenile Pacific fulmars (most two to four months after fledging) dominated the samples and had statistically significant higher plastic loads than older birds (immatures and adults) and for that reason should not be compared to Atlantic studies with different age composition. Unfortunately, Shugart and Nania (2021) provided no overall average mass and no EcoQ% and for that reason their data could not be included in Table 2 and Fig. 3: however, their %FO was

lower than that found by Terepocki et al. (2017) (Table 2) suggesting a similar or lower EcoQ%.

Unfortunately, most studies have insufficient detail and/or inadequate sample sizes on age composition in the samples to demonstrate significant age effects. Except for the cases mentioned above, other studies in Table 2 did not consider or did not find age differences. Even the large sample from Sable Island was reported to show no effects from age, but necropsy methods and details on age or sex proportions were not provided (Bond et al. 2014).

Our Greenlandic sample fitted in the latitudinal gradient, but when taking into account that in our opinion (Table 1), the majority of birds were adults, a more age balanced population sample might result in a somewhat higher plastic abundance in the larger geographical pattern.

Sex

Among our 145 Greenland birds, assigned sex was significantly related to the ingested plastic mass, with females having more plastic than males. A similar tendency was present in the small sample of dissected birds, but not statistically significant.

Three sets of data for northern Iceland illustrate the variability in incidental samples. Among 121 birds, the data from Snaethorsson (2018, 2019, 2021 and personal information on raw data) average at a very low 0.08 ± 0.03 g of plastic in the stomach, in which no significant effect of age could be shown, but that had a remarkably significant sex difference ($U = 1039.5$; $p = 0.011$) between 87 males (0.03 ± 0.01 g) and 34 females (0.21 ± 0.10 g). In fact, it was the Snaethorsson (2018, 2019, 2021) reports that triggered our interest in sex-related differences in plastic ingestion. With only 13% of the birds having over 0.1 g plastic in the stomach, this Icelandic sample did not statistically differ from the Fulmar-TV. Remarkably, two earlier incidental studies in the nearby Icelandic Westfjords reported average plastic stomach contents of 0.13 ± 0.04 g in 58 longline victims from April 2011 (Kühn and Van Franeker 2012) and 0.12 ± 0.02 g in 40 hunted fulmars from mainly October 2013 (Trevail et al. 2014), both more similar to our Greenlandic sample than to the recent Icelandic monitoring data, but they do not show clear sexual (or age) differences and are significantly above the Fulmar-TV. Due to this, further work in the recently started Icelandic monitoring program is strongly recommended.

Using the North Sea data underlying Van Franeker et al. (2021), Mann–Whitney U test could not detect a significant influence of sex over the 2002–2018 period, nor for the limited 5-years period 2014–2018. However, analysis of the data for the Faroe Islands 2007–2011 from Van Franeker et al. (2013) revealed that 319 males averaged at 0.135 ± 0.0129 g of plastic, compared to 0.157 ± 0.0114 g in

232 females, a significantly lower plastic load in the males ($U=30,774$, $p<0.001$).

In a relatively small sample of 29 fulmars, Baak et al. (2020) observed a significantly lower load of plastic in males than in females. Apart from the studies mentioned above, sources in Table 2 did not consider or find sex differences in plastic ingestion. Most studies on plastic ingestion in seabirds have not taken sex in consideration (Provencher et al. 2017).

Season

Quite a few of the incidental studies in Table 2 have been based on samples taken over a very short time period or fixed season. Our sample from Greenlandic waters was collected on a single day in June. The monitoring programs in the North Sea run through all seasons. However, the start-up of Icelandic monitoring by Snaethorsson (sampling years 2018, 2019, 2020) is restricted to samples collected between mid-March and very early June. The pilot study by Van Franeker and Meijboom (2002) could not detect seasonal influences. However, seasonal summer declines in plastic loads have been observed in stomachs of seabirds after arrival from polluted wintering areas to breeding locations in much cleaner polar environments. This has been documented in Van Franeker and Law (2015) based on Cape petrels (*Daption capense*) in the Southern Ocean (Van Franeker and Bell 1988), and fulmars (Mallory 2008) and Brünnichs guillemots (*Uria lomvia*; Provencher et al. 2010) in the Canadian Arctic. A seasonal aspect should thus be considered in the interpretation of incidental studies or the setup of new monitoring programs.

For example, the Arctic Canadian sample in Baak et al. (2020) consisted of adults shot in early August 2018 and the remarkably low level of plastic ingestion (EcoQ%: 3%) could well be linked to seasonal decline as observed in Mallory (2008). In contrast, the plastic ingestion level found for fulmars from Svalbard (Trevail et al. 2015) seemed relatively high in the light of the far northern latitude. The potential presence of a gyral system in the Barents Sea (Van Sebille et al. 2012) was discussed as potential explanation, but it should be noted that 35 of the 40 birds in this sample were non-adults, suggesting that a more balanced age composition of a local sample might result in a lower plastic level in the population.

Combined effects

In the above, potential variables that might influence plastic mass or EcoQ performance in specific samples were considered in isolation, but of course different variables may interact and might complicate firm conclusions.

Large datasets are needed for a multivariate approach. In the integrated analysis of North Sea fulmar data, Van Franeker et al. (2021) demonstrated in a logistic model that age as covariate significantly contributed to the temporal 2002–2018 decline in the annual EcoQ%. As a next step in the analyses, sex was included, which indicated that females had more plastic than males, however, the additional effect to that of year and age was not significant. When considering the North Sea 2002–2018 data for 2661 fulmars in a Generalized Linear Mixed Model (GLMM), age ($F=16.15$, $p<0.001$), year ($F=13.05$, $p<0.001$) and subregion ($F=6.98$, $p<0.001$) contributed significantly to the mixed model for individual birds being above or below the 0.1 g level of plastic in the stomach. Sex of the birds was not a significant factor ($F=0.08$, $p=0.923$): possibly, the substantial differences between areas where fulmars breed and areas where they are only visitors are a complicating factor. Excluding subregional differences, we also reanalysed the data underlying the Faroe Islands 2007–2011 results reported in Van Franeker and the SNS Fulmar study group (2013): most birds will come from the large local breeding population. Age and sex were known for 551 fulmars. Here, year of collection was not a significant factor ($F=0.16$, $p=0.693$), but both age ($F=11.73$, $p<0.001$) and sex ($F=10.58$, $p=0.001$) were significant factors for birds being under or above the 0.1 g level of plastic in the stomach with adult birds and males being more frequent under the 0.1 g level. Future analyses should attempt to include also seasonal variations.

Explanatory hypothesis

Our hypothesis on the effects of age (adults less plastic) and sex (males less plastic) and season (decreasing plastic after arrival in clean environment) on the quantity of plastic in the stomach is that they may all relate to differential nest-site attendance. In general, fulmars tend to not regurgitate indigestible hard remains of prey and plastics, but process these in their stomachs. After initial processing of food in the first large glandular stomach (the proventriculus) the food passes to the muscular gizzard where hard diet items, including plastics, temporarily accumulate to be gradually ground down to a size that may pass into the gut.

When attending the colony, disputes over nest-sites or defense against predators may force birds to occasionally spit stomach oil from their proventriculus against competitors or attackers (Fig. 4). If a spitting bird has plastics in its proventriculus, it may lose some of this plastic with the oil. The same seasonally applies to adults feeding their chicks. It is not expected that defensive spitting or feeding chicks would affect plastics in the muscular gizzard where most plastics accumulate: the narrow passage between proventriculus and



Fig. 4 The fouled fulmar on this photo had probably been spat on by its angry neighbour to the left in a dispute over the nest-site. The yellow colour of the oil indicates a fishy diet as crustacean diet usually leads to more orange colour of the oil (photo taken Iceland 3 July 2018 by Jan van Franeker)

gizzard prevents return of plastics once they have entered the gizzard (Ryan and Jackson 1986).

Considering colony attendance in relation to age, young fulmars under breeding age are known to stay out at sea for several years before returning to the colony to gradually establish a partner bond and nest-site ownership. Fulmars start breeding at the mean age of 9.2 years (males 8.4; females 10.3 years (Ollason and Dunnet 1978). When they first start visiting land is not exactly known, but for sooty shearwaters (*Puffinus griseus*), Fletcher et al. (2013) reported that the first return to the colony was at age of 4.8 years, about 3 years before the first breeding (7.7 years). An early analysis of plastics in fulmars from the Faroe Islands (Jensen 2012) had shown that plastic abundance in non-adult birds showed a stepwise decrease from fledglings to 1st year juveniles, to 2nd year birds and finally to immatures and adults. An initial truly pelagic lifestyle of younger birds with land visits only gradually increasing in later years could explain higher average plastic loads in younger birds, gradually decreasing to adulthood.

We have only gradually become more aware that in addition to age, there are sex-related differences in colony attendance, foraging distributions and trip durations. In the long-term study colony on Eynhallow (Orkney Islands, Scotland), the median duration of female absence during trips to sea changed from 595 h in the pre-laying exodus, to 175 h during incubation to 21 h when feeding the chick. In males, these trip durations were 432, 111, and 20 h, respectively, so considerably shorter except during chick feeding. Median distance from colony during the pre-laying exodus was nearly 500 km further out for females than for males. During egg incubation, exceptional long travel has been

reported (Edwards et al. 2013), but the median distances to the colony were 702 km for females and 476 km for males, to be reduced during chick feeding to around 60 km for both sexes (Edwards 2015; Edwards et al. 2016). During the post-breeding moult period, Grissot et al. (2020) estimated the median distance to the colonies increased to around 1900 km for females, but only 500 km for males. Quinn et al. (2016) showed a graph on monthly mean proportions of time spent ‘dry’ measured by activity loggers. These measurements reflect time spent on land, which showed that males of breeding age spent more time dry than females during most parts of the year except the actual breeding period. Thus, throughout most of the year, adult males forage nearer the colonies and spend more time at the nest site than females. If more frequent and longer nest attendance by males is associated with more frequent spitting of stomach oil, this could explain a difference in average plastic mass in stomachs of males as compared to females.

The extreme sex difference in the 2018–2020 Icelandic study might find an explanation in seasonal variation in colony attendance of males and females. Data illustrated in Fig. 1 of Quinn et al. (2016) showed that male preponderance in colony attendance occurred in most non-breeding months of the year, but was exceptionally strong in April and May, when the bulk of the 2018–2020 Icelandic fulmars was collected (Snaethorsson 2018, 2019, 2021). If this indeed has played a role, the important message is that seasonal variations between samples are a further important variable to consider in the planning of future monitoring projects.

Conclusion

We have provided a new datapoint in the geographical pattern of plastic ingestion by northern fulmars. There is a significant latitudinal pattern in both the North Atlantic and North Pacific, with less plastics in the stomachs further north, at greater distances from industrialised and densely populated areas. We have shown that abundance of plastic in an individual sample may vary substantially with variables like age or sex and possibly the season of collection. These variations do not overrule the significant latitudinal pattern, but they can explain local deviations. Increased awareness of factors potentially influencing plastic abundance in fulmar stomachs is thus of importance when evaluating incidental studies or when planning new monitoring projects. Such variables do not impair the monitoring data collected in large and long-term studies. In a consistent sampling regime, temporal trends can be perfectly analysed using all data, as shown in the North Sea fulmar monitoring program (Van Franeker et al. 2021) where age variations are mainly considered as background information to linear trends of individual data. Predictions for annual EcoQ Performance

may include the effects of additional variables: Van Franeker et al. (2021) did include age as a covariate in their predictive annual trend model, but did not include sex proportions, because no additional significant contribution of sex could be demonstrated. However, an approach of required additional significance is debatable, as inclusion of further variables could improve the overall accuracy of the model, even if not individually significant. We strongly recommend further work to evaluate the hypothesis that both age- and sex-dependent variations in plastic loads may have a background in differential colony attendance and that further aspects, such a seasonal effects, could play an additional role.

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Author contributions JAF: initiative, laboratory, data processing and analysis, lead author; JKJ: initiative, sample handling, writing; PJS: fieldwork; EBR: laboratory and writing; SK: analysis, literature and writing.

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Availability of data and materials All relevant data are included in tabular format in the Electronic Supplementary Material (ESM). Plastics from the stomach samples are stored at Wageningen Marine Research in Den Helder the Netherlands. For further info, contact Jan van Franeker or Susanne Kühn.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest or competing interests.

Ethics approval At the time of fulmar collection in June 2015, the hunter thought that his capture of fulmars at the offshore location required no special permit (100 km off the nearest coast; at 650 and 870 km distance from Greenland's nearest breeding colonies). We learned only later that hunting of fulmars, also in the offshore sector of the Greenlandic EEZ, was unauthorized except for the months of September and October. Since we felt that it had no purpose to dis-

card the valuable study material, we requested permission from the Greenlandic Government to publish our results of the stomach analyses in spite of the illegal character of the hunt. This permission was kindly provided by the Ministry of Fisheries and Hunting (20 Dec 2021, Case nr 2021–76, Akt nr. 18824778). The seasonal restriction of fulmar hunting in Greenland was adopted because near colonies, in September–October, the traditional hunt of fledglings has a relatively low population impact. Our study results show that the same line of reasoning has validity also in the offshore sector. A considerable proportion of our study birds were active adult breeding birds, likely not from Greenland, but probably linked to the large Icelandic population.

Consent to participate All authors.

Consent for publication All authors.

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