Marine Pollution Bulletin 215 (2025) 117894

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Plastics in stomachs of northern fulmars (*Fulmarus glacialis*) collected at Flemish Cap, Grand Banks of Newfoundland

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ARTICLE INFO

Keywords:
Plastic ingestion
Fulmar-threshold-value FTV
Geographical pattern
North Atlantic Ocean
Ocean currents
Latitude
Sea surface temperature SST

ABSTRACT

Incidental studies of plastic ingestion by the northern fulmar (*Fulmarus glacialis*) over a wide geographical range can improve our understanding of the distribution of marine litter in the global oceans and of the processes involved. A sample of 37 stomachs from northern fulmars (*Fulmarus glacialis*) collected in June 2021 near Flemish Cap at the eastern end of the Grand Banks of Newfoundland was analysed for the presence of plastic litter. Overall, 89 % of the birds contained plastic, with on average 6.6 particles, and a mass of 0.093 g per bird. No statistical differences were found in the quantity of plastic between males and females. A proportion of 27 % of all birds contained >0.1 g plastic, exceeding the Fulmar Threshold Value (FTV%) and international target of <10 %. Within an existing model that linked plastic abundance to latitude, the Newfoundland sample represented a clear outlier with a considerably lower FTV% compared to what would be expected. Flemish Cap is situated at the border between the southern tip of the cold and relatively clean Labrador Current coming from the north, and the warm and more polluted waters of the Gulf Stream further south. A logistic model using average annual sea surface temperatures representing North Atlantic current systems was applied and demonstrated a highly significant correlation, with the Newfoundland FTV% fitting much closer to the modelled prediction. This new model improves the understanding of geographical patterns in plastic uptake by fulmars.

1. Introduction

Plastic pollution poses a serious threat to marine ecosystems worldwide. Wildlife can suffer major consequences via entanglement and ingestion (Kühn and Van Franeker, 2020). Despite growing awareness of such problems, plastic production continues to increase and was estimated to exceed over 1 billion tonnes of plastic annually by 2060 (OECD, 2022). In perspective, this is compared to an annual production of 400 million tonnes (Mt) in 2022 and a mere 1.5 Mt. in 1950 (PlasticsEurope, 2023). Annually, a substantial 4.8 to 12 Mt. of plastics may be lost to the oceans from landbased sources (Jambeck et al., 2015). OECD (2022) reports a similar 6.1 Mt. annually leaking into aquatic environments plus 1.7 Mt. directly lost to the oceans. Over the years, OECD (2022) estimates that 139 Mt. of plastic litter has accumulated in rivers and oceans. This emphasizes the urgency to establish effective solutions to reduce plastic production and plastic waste, unintended loss and direct discards.

Several policy measures have been developed to reduce the amount of plastic waste that ends up in the ocean. In 2002, OSPAR introduced a system of Ecological Quality Objectives (EcoQO's) to monitor the health of the marine system (North Sea Ministerial Conference, 2002). In relation to the issue of marine litter, OSPAR developed an EcoQO for the North Sea that used plastics in stomachs of northern fulmars (*Fulmarus glacialis*, from here on 'fulmar') as a monitoring tool for marine plastic debris (OSPAR, 2008, 2015). The fulmar is an abundant seabird found throughout the North Atlantic and North Pacific oceans (Mallory et al., 2012). Because this species regularly ingests plastic, feeds exclusively at sea, and usually does not regurgitate indigestible prey remains, it has been selected as a suitable candidate to provide information about litter pollution in a certain area and timeframe (Van Franeker and Meijboom,

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https://doi.org/10.1016/j.marpolbul.2025.117894
Received 22 October 2024; Received in revised form 24 March 2025; Accepted 25 March 2025
Available online 29 March 2025

2002). The monitoring methodology has been firmly established in international guidelines (OSPAR, 2015). Gradually, OSPAR fulmar studies and their policy target of <10 % of stomachs containing >0.1 g of plastic, have been accepted in the wider EU MSFD (Marine Strategy Framework Directive; EC, 2022). The OSPAR EcoQ Objective is now generally addressed as the Fulmar Threshold Value (acronym 'FTV'; Van Franeker et al., 2021).

Plastic ingestion patterns of the fulmar along the Dutch coast have been documented as far back as the early 1980's (Van Franeker, 1985). Since 2002, all countries around the North Sea have participated in the monitoring (Van Franeker et al., 2011, 2021) and more and more studies in the North Atlantic and North Pacific Oceans apply the Fulmar Threshold Value approach (e.g., Provencher et al., 2017, Avery-Gomm et al., 2012, see Supplement Table 3 for a full list of studies). Together, these studies are crucial for understanding regional pollution levels and the processes that drive litter distribution across vast oceanic areas. Kühn and Van Franeker (2012) first tested the hypothesis that the amount of marine litter decreases with higher latitudes in the Atlantic. They found that the examined sample of Icelandic northern fulmars fitted in a pattern whereby North Sea fulmars had the highest plastic content, followed by those from the Faroe islands, then Iceland, and finally, the least plastic was found in birds from Arctic Canada. The pattern of pollution appeared to correlate with latitude and related human coastal and marine activities that result in considerable input of plastic waste (Kühn and Van Franeker, 2012). Local deviations have been observed, for example Trevail et al. (2015) found that fulmars from Svalbard contained more plastics than would be expected by the latitudinal model. This illustrates that the geographical pattern of marine plastic pollution is not yet fully understood. In order to improve such understanding OSPAR's Intersessional Correspondence Group of Marine Litter (ICG-ML) is currently considering an extension of its monitoring programme for marine litter in stomachs of fulmars to the Arctic region with programs from Norway, Iceland and Denmark.

This paper adds a new datapoint in the geographical pattern of plastic ingestion for fulmars, derived from fulmars collected in the offshore waters of Flemish Cap at the eastern end of the Grand Banks of Newfoundland (from here on 'Newfoundland Banks', acronym NFB). Newfoundland and Labrador have small fulmar breeding colonies (Nettleship and Montgomerie, 1974) and plastic ingestion by fulmars near these colonies was studied by Avery-Gomm et al. (2018). The international waters far off the Newfoundland coast are known to be an important feeding ground for many fulmars from the large North Atlantic fulmar populations (Brown, 1970; Amélineau et al., 2021; Dehnhard, 2022). By analysing fulmar stomachs from these offshore waters, we aim to further improve knowledge of the geographical pattern of plastic ingestion by fulmars and thereby on the processes involved in pollution levels across the North Atlantic Ocean.

2. Materials and methods

On the 11th of June 2021, a sample of 37 northern fulmars was collected from the Faroese fishing vessel Arctic Viking, targeting shrimps near Flemish Cap at the eastern end of the NFB, at position 48.33°N – 45.25°W (Fig. 1). This location is situated in international

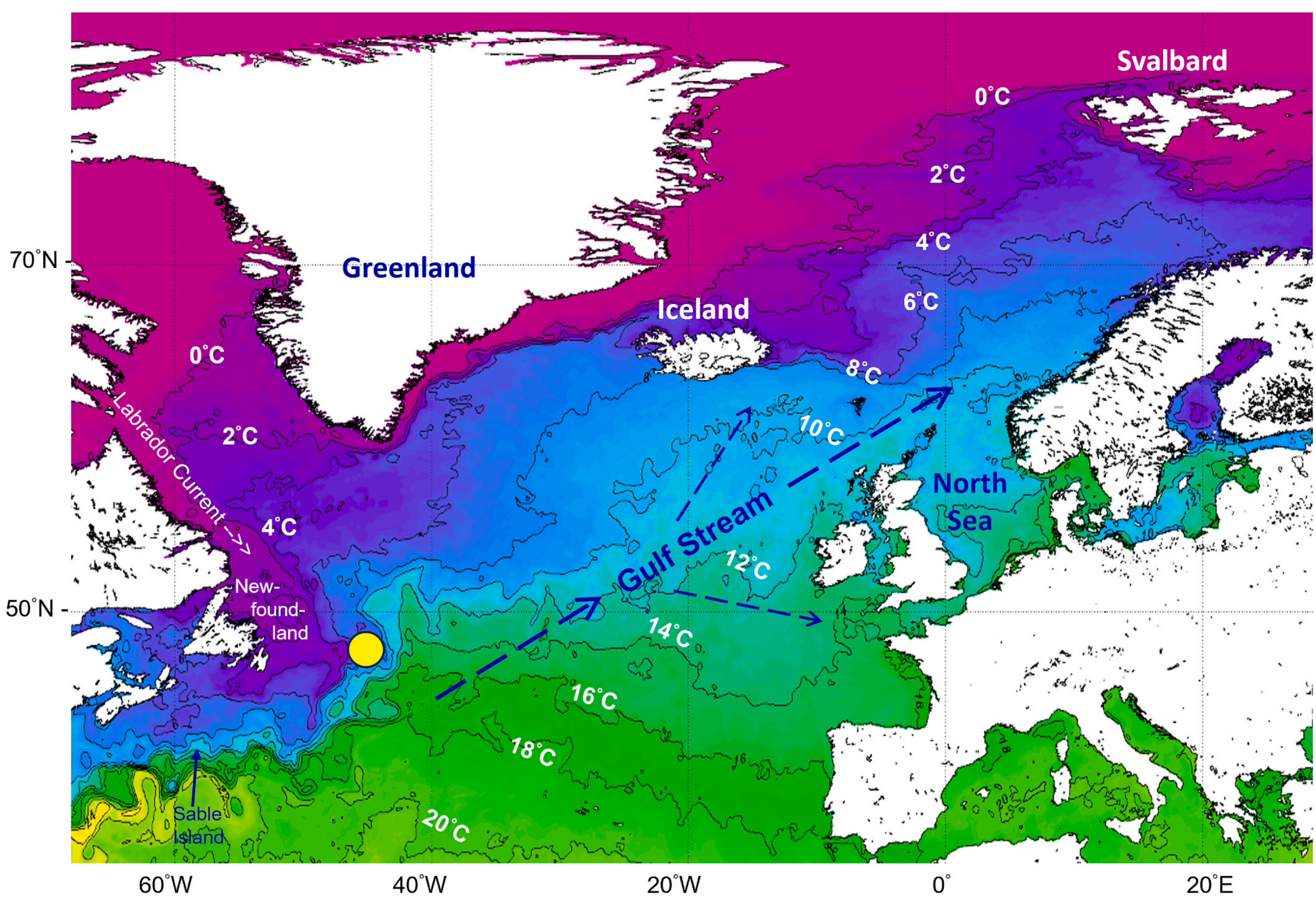

Fig. 1. Position of the NFB sampling location in the North Atlantic Ocean in the context of geographical latitude, major ocean currents and Sea Surface Temperature (SST) gradients in early June 2024 (adapted from https://www.ospo.noaa.gov/data/sst/contour/global.c.gif; version June 7, 2024). The yellow circle shows the sampling location at Flemish Cap. The NFB have an average annual SST of around 2 °C to 4 °C, but are close to a sharp border with much warmer water in the Gulf Stream. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

waters, 560 km (302 nm) off the Canadian coast. Arctic Viking was fishing by bottom trawling at about 400 m depth. Fulmars concentrated around the ship because net losses and discards of shrimps and small fishes provided attractive prey. The birds were caught for human consumption with a long-handled net (fleyg; Jensen, 2012). Corpses were skinned and cleaned on board, but the heads, along with the attached oesophagus, stomachs, and in many cases the intestines were preserved for research and kept frozen until they could be examined.

Biometric head measurements were taken in order to assign probable sex by calculating a discriminant score (Van Franeker and Ter Braak, 1993). The three available head measurements for the NFB fulmars are head length (HB), culmen length (CL), and bill depth at gonys (BD2). An update of the original discriminant program provided by Van Franeker and Ter Braak (1993) was given in Van Franeker et al., (2022). Instead of the small source file for different species of fulmarine petrels used in Van Franeker and Ter Braak (1993) and Van Franeker et al.,. (2022), we now based the discriminant formula on the very large set of data for all northern fulmars from the North Atlantic measured and sexed by Van Franeker and Kühn ($n = 3451$). The generalized discriminant formula using the three available head-measurements was: WG3Atl = HB+ (0.8056*BD2) + (-0.4497*CL). Cutpoints were separately specified for double light fulmars (colourphase LL) as cutpoint = 91.49211; and for coloured fulmars (colourphases L, D, and DD) as cutpoint = 89.15922. Colouration of the current sample was derived from yes or no grey feathering on top of head and upper part of the neck. High Arctic coloured breeding populations *(Fulmarus glacialis glacialis)* are smaller sized than the double light fulmar populations (*F. g. auduboni*) breeding mostly in lower Arctic and temperate zones (Van Franeker and Wattel, 1982; Van Franeker, 1995). A mix of these subspecies may occur in any offshore oceanic area of the North Atlantic, including the seas off Newfoundland and Labrador (Brown, 1970; Amélineau et al., 2021; Dehnhard, 2022). Using the colour-specific cutpoints, the discriminant score assigned 93.7 % of 3451 North Atlantic fulmars to the correct sex. Similar reliability of assigned sex in the sample of birds from the NFB may be expected.

The proventriculus, gizzard, and when available the intestines were separately examined by standard methods of the fulmar monitoring program (e.g. OSPAR, 2015; Van Franeker et al., 2021). The stomachs were cut open and contents were rinsed in cold tap water using a sieve with a 1 mm mesh size. Contents were examined using a binocular microscope and sorted into marine litter, natural food, and natural non-food items. Plastics were split into different subcategories (industrial plastics, and user plastics comprising of sheets, threads, foams, fragments and other plastics), after which they were counted and weighed using an electronic Sartorius weighing scale with an accuracy of 0.0001 g. When subcategories weighed as 0.0000 g, they were considered to weigh 0.0001 g. The polymer composition of all plastic items was identified by Fourier Transform Infrared Spectroscopy (FTIR) analysis, using the Shimadzu IRSpirit and the integrated software program. Polymer compositions were accepted when reliability was over the 80 % threshold (Kühn et al., 2021). Some items were cut in half, or sliced or scraped along the surface in order to provide a clear surface for the FTIR measurement. Pressure on particles caused fragmentation of some of them. For these reasons there may seem occasional discrepancies between numerical details in Supplement Table S1 and the photos of samples in the Supplement.

The intestines that could be preserved were cut in fragments and treated with 1 M potassium hydroxide (KOH) in glass jars. The KOH solution efficiently digests most of the organic material, while preserving the mass, morphology, and chemical integrity of most plastic polymers (Kühn et al., 2017; Karami et al., 2017; Dehaut et al., 2016). The samples were then placed in a shaking bath set to 120 rpm at a temperature of 35 °C for seven days. The remaining contents were sieved over a 1 mm mesh and analysed in the same way as stomach contents.

The data for both mass and number of plastics were not normally distributed. Therefore differences between quantities of plastics ingested related to sex and stomach compartments were tested using the non-parametric Mann-Whitney *U* test (Genstat 22nd edition; VSN International, 2017). To compare proportions between samples with respect to the frequency of occurrence (FO%) and the FTV% for birds exceeding the Fulmar Threshold Value of 0.1 g of plastic in the stomach, the Epitools *Z*-test was used (https://epitools.ausvet.com.au/ztesttwo). Lastly, a logistic General Linear Model (GLM) approach (Genstat 22nd edition) based on binomial proportions was used to determine the presence of potential trends for FTV% in relation to latitude and sea surface temperatures. A General Linear Mixed Model (GLMM; Genstat 22nd edition) was used to evaluate the combined effect of both variables. Annual averages for sea surface temperatures were derived from https://atlas.climate.copernicus.eu/atlas/lmoCdxCm. A map of early June sea surface temperatures (the period of our sampling) was derived from https://www.ospo.noaa.gov/data/sst/contour/global.c.gif. The logistic regression analysis uses a logit transformation based on the number of fulmars in the sample and the number of fulmars exceeding the FTV, in relation to an environmental variable such as latitudinal position or average sea surface temperature. For all tests, the statistical significance level was set at $p < 0.05$.

3. Results

Based on the entire sample of 37 fulmars, the average number of plastics with standard error was 6.6 ± se 1.2 particles, with an average total mass of 0.093 ± 0.024 g (Table 1). Plastic items were found in 33 of 37 birds (%FO: 89 %). Ten of the 37 stomachs (27 %) exceeded the FTV criterion of containing >0.1 g of plastic.

The discriminant score from head measurements led to the assignment of 14 females and 23 males in our NFB sample. Due to the type of sample (head + digestive system only), age could not be assessed. Most fulmars were of the LL colourphase, there were only two coloured birds, one female and one male. Individual details on measurements, discriminant scores and assigned sex are provided in Supplement Table S1. None of the differences between the sexes in plastics ingested were statistically different in Mann-Whitney *U* tests and Epitools Z tests. Significantly more plastic was found in the gizzard compared to the proventriculus, for both mass and number (Mann-Whitney U test $p < 0.001$), whereas in the 22 available samples of intestines zero plastic particles were detected (Table 1B).

Fulmars contained significantly more user plastics than industrial plastics by number and mass (Mann-Whitney U test $p < 0.001$). This was evident for separate sexes and different parts of the digestive system (Table 2). User plastics represented about 94 % of the total plastic mass, largely made up by fragments (Supplement Table S2). For individual birds, detailed information on the presence of different categories and subcategories of plastics in the stomachs is provided in Supplement Table S2 and photos. The FTIR analyses revealed that more than half (52 %) of all 245 plastic items found were classified as polyethylene (PE), followed by a substantial proportion (19 %) polypropylene (PP).

Within the NFB sample, 27 % of the birds exceeded the Fulmar Threshold Value of 0.1 g of plastic in the stomach. The FTV% datapoint for the NFB sample and for other recent sources listed in Table S3 were added in a new run of the logistic model created by Van Franeker et al. (2022) which illustrated a latitudinal decline in ingested plastics (Supplement Table S3; Fig. 3). The Generalized Linear Model (GLM) logistic regression of the binomial proportions of fulmars in the studies exceeding 0.1 g of plastic demonstrates a significant negative correlation with the latitude at which they were collected ($p < 0.001$, Supplement Table S4). Although this correlation was found to be significant, Fig. 3 demonstrates that our current study (datapoint in yellow) is a clear outlier with a considerably lower FTV% compared to what would be expected at this latitude according to the logistic model.

The latitudinal model had its origin in the situation in the eastern North Atlantic, with densely populated and industrialized areas in the south and gradually lower levels of human influences when moving to

Table 1
Presence of plastic in the stomachs of 37 NFB fulmars, subdivided by A. sex and B. different parts of the digestive system. Shown are the proportion of birds with plastic in the stomach (%FO, frequency of occurrence), average number and mass with standard error, median mass, geometric mean mass and proportion of birds containing >0.1 g of plastic (FTV%).

A.	Sample		Average number	Average mass	Median	GEOMETRIC	
	n	%FO	n ± se	g ± se	Mass (g)	Mean (g)	FTV%
All	*37*	89 %	6.6 ± 1.2	0.093 ± 0.025	0.042	0.0266	27 %
Female	*14*	100 %	5.9 ± 1.8	0.079 ± 0.022	0.059	0.0414	36 %
Male	*23*	83 %	7.0 ± 1.7	0.101 ± 0.038	0.042	0.0202	22 %

B.	Sample		Average number	Average mass	Median	GEOMETRIC	
	n	%FO	n ± se	g ± se	Mass (g)	Mean (g)	FTV%
Proventriculus	*37*	11 %	0.2 ± 0.1	0.002 ± 0.002	0.000	0.0002	0 %
Gizzard	*37*	89 %	6.4 ± 1.1	0.091 ± 0.024	0.040	0.0264	27 %
Intestines	*22*	0 %	0.0 ± 0.0	0.000 ± 0.000	0.000	0.0000	0 %

Table 2
Types of plastic items, subdivided into industrial granules and user plastics (sheets, threads, foams, fragments and other plastics), found in the stomachs of 37 NFB fulmars, subcategorized by A. sex and B. different parts of the digestive system.

		Industrial plastics			User Plastics		
A.	Sample		avg number	avg mass		avg number	avg mass
	n	%FO	n ± se	g ± se	%FO	n ± se	g ± se
All	*37*	27 %	0.4 ± 0.1	0.009 ± 0.003	89 %	6.2 ± 1.1	0.083 ± 0.022
Female	*14*	21 %	0.4 ± 0.3	0.009 ± 0.005	100 %	5.5 ± 1.6	0.070 ± 0.018
Male	*23*	30 %	0.4 ± 0.2	0.009 ± 0.004	83 %	6.6 ± 1.6	0.091 ± 0.034

		Industrial plastics			User plastics		
B.	Sample		avg number	avg mass		avg number	avg mass
	n	%FO	n ± se	g ± se	%FO	n ± se	g ± se
Proventriculus	*37*	3 %	0.0 ± 0.0	0.001 ± 0.001	11 %	0.2 ± 0.1	0.001 ± 0.001
Gizzard	*37*	27 %	0.4 ± 0.1	0.009 ± 0.003	89 %	6.0 ± 1.1	0.082 ± 0.022
Intestines	*22*	0 %	0.0 ± 0.0	0.000 ± 0.000	0 %	0.0 ± 0.0	0.000 ± 0.000

the north. In detail, the observed trend was somewhat contradicted by results of Trevail et al. (2015) who found that birds from Svalbard contained more plastic than would be expected in comparison to the low levels observed in the Canadian Arctic at similar latitudes (Fig. 1, Supplement Table S3). The explanation for this difference between the eastern and western side of the Atlantic may be found in ocean currents that may play an important role in transporting plastic waste over vast distances. The warm Gulf Stream carries water from the Gulf of Mexico, along the United Kingdom and Norwegian coast all the way to the Arctic Ocean (Van Sebille et al., 2012; Cózar et al., 2017; Halsband and Herzke, 2019). In contrast, in the western North Atlantic, the Labrador Current carries cold polar waters southwards to the Newfoundland area. It originates in sparsely populated and non-industrialized Arctic areas further north, and may be expected to be relatively clean. The opposite currents are clearly reflected in Fig. 1 showing sea surface isotherms in early June, around the date when the fulmars from the NFB were collected.

In order to create a logistic model similar to that in relation to latitude but which reflects these ocean current patterns, we assessed the average annual sea surface temperatures in the vicinity of all available datasets on plastic ingestion by fulmars (Supplement Table S3). We used average annual temperatures because the fulmar data sets are highly variable, some covering fulmar collections throughout the year, some only for specific seasons, and some even on a single date. Fig. 4 shows the highly significant correlation ($p < 0.001$) of the logistic regression for FTV% in relation to the annual SST (Table S5). In this analysis, the NFB sample is much closer to the modelled gradient in SST than when related to latitude. There are still other samples that deviate from the model, most strongly so for the data for Ireland (Acampora et al., 2016), but this was a relatively small sample of only 14 fulmars, which may not be representative.

Both the latitudinal (Fig. 3) and SST (Fig. 4) logistic GLM model reveal highly significant ($p < 0.001$) correlations to the quantities of plastic (FTV%) found in fulmar stomachs. Latitude and SST covary in a complicated manner, but when evaluating both factors in a GLM-Mixed model, it becomes clear that SST represents the dominant element ($p < 0.001$) with an insignificant additional contribution of latitude ($p = 0.367$) to the mixed model.

4. Discussion

In the NFB fulmars, the average mass of ingested plastic, and the proportion of birds exceeding the 0.1 g level (FTV%) were considerably lower than predicted by the model for correlation between latitude and the FTV% in Van Franeker et al., (2022). This was the case for both males and females, with no significant difference in the quantity of plastics in the stomach between the sexes. Whether the NFB samples were influenced by age of the birds involved remains unclear, but likely the sampled fulmars consisted of a mix of different ages and different areas from all over the North Atlantic area. Nearly all the NFB birds were of the double light colourphase (LL). Only two birds were of the coloured morphs which occur in the Canadian Arctic and the high Arctic populations in the far north and east of the north Atlantic Ocean (Van Franeker and Wattel, 1982; Van Franeker, 1995). The majority of the NFB birds likely originate from the large LL populations in the temperate to low Arctic regions of the Atlantic such as Iceland, Jan Mayen, the

Fig. 2. Example of one of the heavier plastic loads found in stomachs from the NFB (sample NFB-2021-016, with 0.6534 g of plastic). See Supplement for photos of all NFB stomach samples.

Faroe Islands and the UK and from west Greenland (Brown, 1970; Amélineau et al., 2021; Dehnhard, 2022).

Along the eastern side of the North Atlantic, the pattern of decreasing plastics from the French English Channel up to the Arctic indicates that part of the plastics entering the water in the southern areas, is not detected further north (Isobe and Iwasaki, 2022; Kaandorp et al., 2023). Such decrease may be caused by many factors (Andrady, 2015) like sinking to deeper water, deposition in the ocean bottom or coastal sediments, being blown onshore, fragmentation and degradation by animal ingestion, mechanical- and light degradation, or even degradation by micro-organisms. Along the western side of the North Atlantic, the clean Arctic Labrador Current bounces against the warm and polluted waters of the Gulf Stream (Ma et al., 2022). Fulmars in the NFB area may easily travel the relatively short distance from the polluted Gulf Stream water to the cold and clean water of the Labrador Current, which could explain rather outlying high values seen in two samples NFB-2021-016 (Fig. 2) and NFB-2021-029. Fulmars collected on beaches of Sable Island differ hugely from the NFB fulmars having much higher loads of plastics ingested, on average 26 items weighing 1.09 g (Bond et al., 2014), while being only a few hundred kilometres further south. Such rapid changes in the Sea Surface Temperature (SST) or ingested plastics in fulmars are not found along the eastern side of the North Atlantic.

5. Conclusion

By adding a new datapoint of plastic ingestion by fulmars this paper provides valuable information regarding geographical patterns in marine litter pollution levels. Because of the poor fit of the NFB datapoint in the existing latitudinal model, we looked into the effects of ocean currents and created a similar model using sea surface temperatures. This model shows a gradient with fewer fulmars with >0.1 g of plastic at lower sea-surface temperatures. Like the earlier latitude model we believe this to be a consequence of distance to densely populated and industrialized source areas and transport of litter by oceanic currents. The eastern Atlantic currents flow northwards, while in the western sector they run in the opposite direction.

The models presented in this paper are possible because a diverse community of scientists from widely separated regions use standardized methods for assessing plastics in fulmars (OSPAR, 2015). Standardization in this type of research allows large-scale analyses across both time and space (Provencher et al., 2019). When looking into further detail than just the FTV%, many variables other than just sample size may affect results, such as substantial sex and age differences between samples, seasonality, type of collection, and spatial limits of collection (Van Franeker et al., 2022). Current knowledge is insufficient to include such details as covariates in the models, but continued research may prove very useful.

CRediT authorship contribution statement

Sterre de Bruin: Writing – review & editing, Writing – original draft, Investigation, Data curation. **Jan A. van Franeker:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **André Meijboom:** Writing – review & editing, Supervision, Investigation, Formal analysis. **Jens-Kjeld Jensen:** Writing – review & editing, Resources, Conceptualization. **Bjarni Jacobsen:** Writing – review & editing, Resources. **Susanne Kühn:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation.

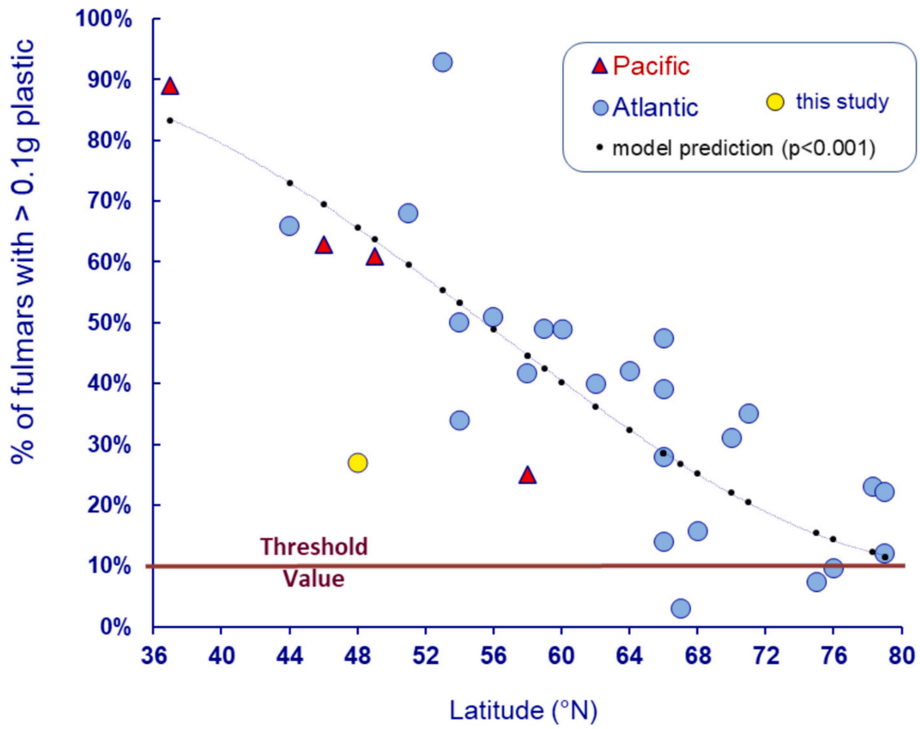

Fig. 3. Logistic model of the percentage of fulmars containing >0.1 g plastic (FTV%), plotted against the latitudes of sampling locations from various studies. Pacific studies are represented as red triangles and Atlantic studies as blue circles. The result from the current study at the NFB is depicted as the yellow circle. The dotted line demonstrates the modelled prediction for expected percentages along different latitudes (see Supplement Table S3 for details and References). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

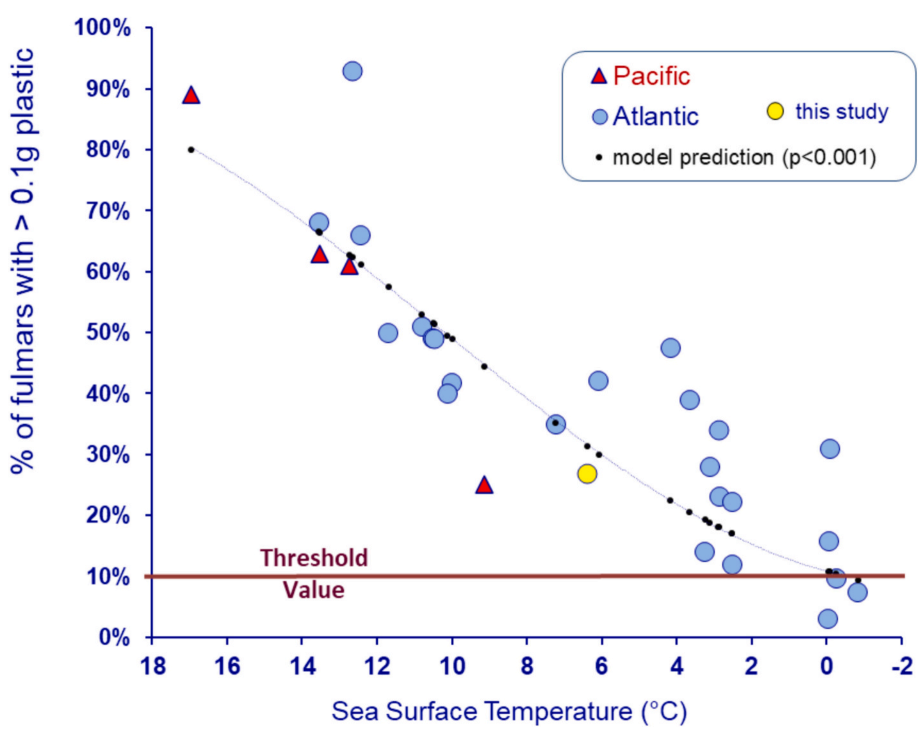

Fig. 4. Logistic model of the percentage of fulmars containing >0.1 g plastic plotted against the annual average Sea Surface Temperature (SST) of sampling locations from various studies. Pacific studies are represented as red triangles and Atlantic studies as blue circles. The result from the current study is depicted as the yellow circle. The dotted line demonstrates the modelled prediction for expected percentages along different water temperatures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Funding Information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

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

Acknowledgements

We thank captain and crew of the vessel Arctic Viking for their help in collecting and storing our samples. At the Faroe Islands we received much appreciated assistance from Jóhannis Danielsen and Bergur Olsen (Marine Research Institute), Sjúrður Hammer (Environment Agency), Janus Hansen (National Museum) and Marita Gullklett. Daniel Turner kindly assisted in a grammatical check. Suggestions by three anonymous reviewers and the editor made a significant contribution to this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.117894.

Data availability

The data underlying this article are available in the article and in its online supplementary material.

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Supplement to

Plastics in stomachs of northern fulmars (*Fulmarus glacialis*) collected at Flemish Cap, Grand Banks of Newfoundland

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Table S1. *Individual data Newfoundland Banks fulmars 11 June 2021.*

INDIVIDUAL DATA NEWFOUNDLAND BANK FULMARS 11 June 2021

JAFCODE	Head length (HB) mm	Bill depth gonys (BD2) mm	Culmen length (CL) mm	Discriminant score (G3Atl)	Assigned sex	colour phase	nr industrial pellets (NIND)	Mass industrial pellets (GIND, g)	nr user plastic (NUSE)	mass user plastic (GUSE)	nr total plastic (NPLA)	msas total plasic (GPLA)	Proventriculus nr (PNPLA)	Proventriculus mass (PGPLA)	Gizzaard nr (GNPLA)	Gizzard mass (GGPLA)
NFB-2021-001	103.0	18.0	42.2	98.5235	M	LL	0	0.0000	5	0.0417	**5**	**0.0417**	0	0.0000	5	0.0417
NFB-2021-002	97.6	17.6	41.0	93.3409	M	LL	0	0.0000	8	0.0424	**8**	**0.0424**	1	0.0027	7	0.0397
NFB-2021-003	97.6	17.7	38.4	94.5906	M	LL	1	0.0205	7	0.2004	**8**	**0.2209**	0	0.0000	8	0.2209
NFB-2021-004	99.2	17.4	41.0	94.7797	M	LL	0	0.0000	1	0.0001	**1**	**0.0001**	0	0.0000	1	0.0001
NFB-2021-005	96.0	16.6	37.8	92.3743	M	LL	0	0.0000	0	0.0000	**0**	**0.0000**	0	0.0000	0	0.0000
NFB-2021-006	93.4	16.6	39.5	89.0098	F	LL	0	0.0000	2	0.0773	**2**	**0.0773**	0	0.0000	2	0.0773
NFB-2021-007	93.6	16.5	40.0	88.9044	F	LL	2	0.0464	6	0.0807	**8**	**0.1271**	0	0.0000	8	0.1271
NFB-2021-008	98.8	18.3	39.8	95.6444	M	LL	0	0.0000	12	0.0359	**12**	**0.0359**	0	0.0000	12	0.0359
NFB-2021-009	97.7	16.7	41.7	92.4010	M	LL	2	0.0313	8	0.1088	**10**	**0.1401**	0	0.0000	10	0.1401
NFB-2021-010	99.0	18.5	41.9	95.0612	M	LL	0	0.0000	0	0.0000	**0**	**0.0000**	0	0.0000	0	0.0000
NFB-2021-011	98.4	17.0	39.8	94.1971	M	LL	1	0.0218	7	0.0706	**8**	**0.0924**	0	0.0000	8	0.0924
NFB-2021-012	96.5	16.9	40.3	91.9917	M	LL	0	0.0000	2	0.0110	**2**	**0.0110**	0	0.0000	2	0.0110
NFB-2021-013	93.0	16.0	38.3	88.6661	F	LL	0	0.0000	2	0.0255	**2**	**0.0255**	0	0.0000	2	0.0255
NFB-2021-014	96.4	17.6	40.8	92.2308	M	LL	0	0.0000	1	0.0017	**1**	**0.0017**	0	0.0000	1	0.0017
NFB-2021-015	99.8	17.6	39.6	96.1704	M	LL	0	0.0000	5	0.0299	**5**	**0.0299**	1	0.0003	4	0.0296
NFB-2021-016	101.3	18.5	41.5	97.5411	M	LL	2	0.0537	13	0.5997	**15**	**0.6534**	0	0.0000	15	0.6534
NFB-2021-017	97.7	17.4	41.3	93.1448	M	LL	0	0.0000	0	0.0000	**0**	**0.0000**	0	0.0000	0	0.0000
NFB-2021-018	97.2	18.3	40.5	93.7296	M	LL	0	0.0000	0	0.0000	**0**	**0.0000**	0	0.0000	0	0.0000
NFB-2021-019	93.2	16.5	38.0	89.4038	F	LL	1	0.0283	6	0.0919	**7**	**0.1202**	0	0.0000	7	0.1202
NFB-2021-020	98.3	16.3	40.2	93.3533	M	LL	0	0.0000	2	0.0627	**2**	**0.0627**	0	0.0000	2	0.0627
NFB-2021-021	94.0	16.5	39.7	89.4393	F	LL	0	0.0000	1	0.0011	**1**	**0.0011**	0	0.0000	1	0.0011
NFB-2021-022	92.2	15.8	37.5	88.0647	F	LL	0	0.0000	2	0.0401	**2**	**0.0401**	0	0.0000	2	0.0401
NFB-2021-023	97.8	17.1	39.8	93.6777	M	LL	0	0.0000	1	0.0021	**1**	**0.0021**	0	0.0000	1	0.0021
NFB-2021-024	92.2	16.2	36.2	88.9716	F	LL	0	0.0000	2	0.0117	**2**	**0.0117**	0	0.0000	2	0.0117
NFB-2021-025	89.4	14.3	36.3	84.5960	F	LL	3	0.0577	16	0.2478	**19**	**0.3055**	0	0.0000	19	0.3055
NFB-2021-026	96.0	16.0	39.8	90.9915	M	**C**	1	0.0259	10	0.1114	**11**	**0.1373**	0	0.0000	11	0.1373
NFB-2021-027	93.4	16.1	39.3	88.6970	F	LL	0	0.0000	2	0.0044	**2**	**0.0044**	0	0.0000	2	0.0044
NFB-2021-028	89.5	16.1	37.3	85.6964	F	LL	0	0.0000	3	0.0176	**3**	**0.0176**	0	0.0000	3	0.0176
NFB-2021-029	101.5	17.6	43.3	96.2066	M	LL	2	0.0569	34	0.5849	**36**	**0.6418**	4	0.0575	32	0.5843
NFB-2021-030	90.2	16.0	37.0	86.4507	F	LL	0	0.0000	7	0.1213	**7**	**0.1213**	0	0.0000	7	0.1213
NFB-2021-031	93.2	15.7	39.2	88.2197	F	LL	0	0.0000	1	0.0820	**1**	**0.0820**	0	0.0000	1	0.0820
NFB-2021-032	88.2	14.6	35.2	84.1323	F	LL	0	0.0000	5	0.0386	**5**	**0.0386**	0	0.0000	5	0.0386
NFB-2021-033	100.6	17.9	43.7	95.3684	M	LL	0	0.0000	2	0.0032	**2**	**0.0032**	0	0.0000	2	0.0032
NFB-2021-034	100.4	17.9	41.9	95.9778	M	LL	1	0.0083	11	0.0782	**12**	**0.0865**	0	0.0000	12	0.0865
NFB-2021-035	100.8	18.1	40.8	97.0336	M	LL	0	0.0000	11	0.0571	**11**	**0.0571**	0	0.0000	11	0.0571
NFB-2021-036	98.0	17.2	40.9	93.4636	M	LL	0	0.0000	12	0.0590	**12**	**0.0590**	0	0.0000	12	0.0590
NFB-2021-037	92.4	15.0	39.1	86.9007	F	**C**	0	0.0000	22	0.1388	**22**	**0.1388**	3	0.0070	19	0.1318

Table S2. *Types of litter found in the stomachs of 37 fulmars from the Newfoundland Banks, and the abundance per litter category by Frequency of Occurrence (%FO), average number of particles (n/bird ± se), average mass of litter (g/bird ± se), maximum mass and geometric mean mass. User plastics are subcategorized as sheets, threads, foams, fragments, and other plastics.*

NFB 2021 Complete stomachs

NFB 2021 Fulmars	*nr of birds*	*% adult*	*% male*	*% LL colour*
background details	*37*	*unk*	*62%*	*95%*

		%FO	average number of items (n/bird) ± se	average mass of litter (g/bird) ± se	max. mass recorded (g)	geometric mean mass (g/bird)
1	**ALL PLASTICS**	**89%**	**6.6 ± 1.223**	**0.093 ± 0.025**	**0.653**	**0.27027**
1.1	**INDUSTRIAL PLASTIC**	**27%**	**0.4 ± 0.132**	**0.009 ± 0.003**	**0.058**	**0.00154**
1.2	**USER PLASTIC**	89%	6.2 ± 1.145	0.083 ± 0.022	0.600	0.02510
1.2.1	sheets	19%	0.3 ± 0.169	0.001 ± 0.001	0.026	0.00026
1.2.2	threads	41%	0.5 ± 0.120	0.002 ± 0.001	0.029	0.00070
1.2.3	foamed	5%	0.1 ± 0.038	0.000 ± 0.000	0.001	0.00003
1.2.4	fragments	81%	5.2 ± 1.077	0.072 ± 0.021	0.600	0.01782
1.2.5	other plastic	11%	0.1 ± 0.052	0.008 ± 0.004	0.099	0.00055

Table S3. *Data sources used to evaluate the correlations between plastic abundance by Frequency of Occurrence (%FO), average number (n ±se) and mass (g ±se), the percentage of stomachs with plastics above the threshold of 0.1 g (FTV%), the latitude of the location of sampling (Lat N) and the annual average Sea Surface Temperature at that location (avg SST). Locations are sorted according to degrees northern latitude.*

location					*sample*		plastic number	plastic mass			
North Atlantic	**source**	**year(s)**	**season**	**lat-lon range**	***size***	**%FO**	**n ±se**	**g ±se**	**FTV %**	**Lat °N**	**avg SST**
Sable Island	Bond et al. 2014	2001-2012	all year	44°N-59°W	*176*	93%	26.4 ± 2.9	1.09 ± 0.15	**66%**	44	12.4
Newfoundland Banks	this study	2021	Jun	48.33°N - 45.25'W	*37*	89%	6.6 ± 1.2	0.09 ± 0.03	**27%**	48	6.4
Channel area	Van Franeker et al. 2021	2014-2018	all year	51°N-1°E	*22*	86%	24.4 ± 7.6	0.43 ± 0.14	**68%**	51	13.6
Ireland	Acampora et al. 2016	2012-2016	all year	53°N-9°W	*14*	93%	65.4 ± 32.7	1.11 ± 0.57	**93%**	53	12.7
Labrador Sea	Avery-Gomm et al. 2018	2014-2015	Jul	54°N-57°W	*70*	79%	11.6 ± 2.6	0.15 ± 0.03	**34%**	54	2.9
SE North Sea	Van Franeker et al. 2021	2014-2018	all year	54°N-6°E	*240*	93%	20.8 ± 3.0	0.27 ± 0.03	**50%**	54	11.7
UK mainland North Sea	Van Franeker et al. 2021	2014-2018	all year	56°N-1°W	*41*	90%	25.1 ± 5.1	0.17 ± 0.05	**51%**	56	10.8
Skagen	Strand et al. 2023 (original data)	2021-2023	all year	58°N-9E	*24*	79%	86.5 ± 75.0	1.45 ± 0.83	**42%**	58	10.0
Skagerrak Area	Van Franeker et al. 2021	2014-2018	all year	59°N-11E	*37*	97%	19.1 ± 4.3	0.15 ± 0.03	**49%**	59	10.5
Scottish Islands	Van Franeker et al. 2021	2014-2018	all year	60°N-2°W	*53*	87%	21.7 ± 5.6	0.32 ± 0.10	**49%**	60	10.5
Faroe Islands	Van Franeker & the SNS Fulmar Study Group 2013	2007-2011	all year	62°N-7°W	*699*	91%	11.3 ± 0.6	0.15 ± 0.01	**40%**	62	10.1
East Greenland	Van Franeker et al. 2022	2015	Jun	64°N - 36°W	*145*	86%	13.5 ± 1.8	0.14 ± 0.02	**42%**	64	6.1
West Greenland Coast	Strand et al. 2018	2016	summer	±66°N - 54°W	*31*	87%			**39%**	66	3.7
Iceland	Kühn & Van Franeker 2012	2011	Apr	66°N-23°W	*58*	79%	6.0 ± 1.0	0.13 ± 0.04	**28%**	66	3.1
Iceland	Trevail et al. 2014	2013-14	Oct (n=37) Feb (n=3)	66°N-23°W	*40*	90%		0.12 ± 0.02	**48%**	66	4.2
Iceland	Snaethorsson & Brynjolfsson 2023	2018-2023	Mar-Jun	66°N-20W	*194*	72%	5.1 ± 0.1	0.04 ± 0.01	**14%**	66	3.2
High-Arctic Canada south	Baak et al. 2020	2018	Jul	67°N - 62°W	*29*	72%	1.7 ± 1.6	0.02 ± 0.03	**3%**	67	-0.04
High-Arctic Canada south	Van Franeker et al. 2021	2002-2008	Aug-Sep	± 68°N - 62°E	*57*	49%	3.0 ± 0.6	0.05 ± 0.01	**16%**	68	-0.07
West Greenland offshore	Strand et al. 2018	2016	summer	± 70°N -60°W	*32*	84%			**31%**	70	-0.1
North Norway	Herzke et al. 2016	2013	all year	71°N-20°W	*72*				**35%**	71	7.2
High-Arctic Canada north	Van Franeker et al. 2021	2003-2013	May-Aug	± 75°N - 90°E	*122*	40%	2.3 ± 0.5	0.04 ± 0.01	**7%**	75	-0.8
NE-Greenland (76°N)	Ask et al. 2020	2017	Aug-Sep	±74° to 78°N 4°-20°W	*31*	90%	6.2 ± 1.5	0.06 ± 0.02	**10%**	76	-0.3
Svalbard; non fledglings	Trevail et al. 2015	2013; Sep	Sep	78°N-16°E	*40*	88%	15.3 ± 5.5	0.08 ± 0.02	**23%**	78	2.9
Svalbard; non fledglings	Tulatz et al. 2023; non-fledglings	2020, Sep	Sep	79°N-12°E	*18*	89%		0.05 ± 0.02	**22%**	79	2.5
Svalbard; non fledglings	Collard et al.2022	2022; Mar	Mar	79°N-12°E	*43*	91%	10.3 ± 1.8	0.07 ± 0.01	**12%**	79	2.5
North Pacific	**source**	**year(s)**		**lat-lon range**	***n***	**%FO**	**n ±se**	**g ±se**	**coQ%**	**Lat Map**	**avg SST**
California	Nevins et al. 2011	1997-2010	all year	37°N-123°W	*437*	94%			**89%**	37	17.0
Washington / Oregon	Terepocki et al 2017	2008-2013	all year	46°N-123°W	*143*	90%	19.5 ± 2.1	0.46 ± 0.07	**63%**	46	13.5
British Columbia	Avery-Gomm et al. 2012	2009-2010	Oct-Apr	49°N-126°W	*36*	97%	52.9 ± 17.2	0.35 ± 0.09	**61%**	49	12.7
Alaska	Nevins et al. 2011	2005-2009	all year	58°N-145°W	*? (100?)*	63%			**25%**	58	9.1

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Table S4. *Logistic regression for the correlation between percentage of fulmars exceeding the 0.1 g of plastic in the stomach (FTV%) and the latitude (degrees North) of the location of collection.*

Estimates of parameters LATITUDE TEST				antilog of
Parameter	estimate s.e.	t(*)	**t pr.**	estimate
Constant	4.801 ± 0.2	20.83	**<.001**	121.6
latitude	-0.0871 ± 0.0	-22.01	**<.001**	0.9166

* MESSAGE: s.e.s are based on dispersion parameter with value 1.

Table S5. *Logistic regression for the correlation between percentage of fulmars exceeding the 0.1 g of plastic in the stomach (FTV%) and the annual average sea surface temperature (SST) at the location of collection.*

Estimates of parameters SST TEST				antilog of
Parameter	estimate s.e.	t(*)	**t pr.**	estimate
Constant	-2.143 ± 0.1	-21.03	**<.001**	0.1174
avg_annual_SST	0.20671 ± 0.0	21.86	**<.001**	1.23

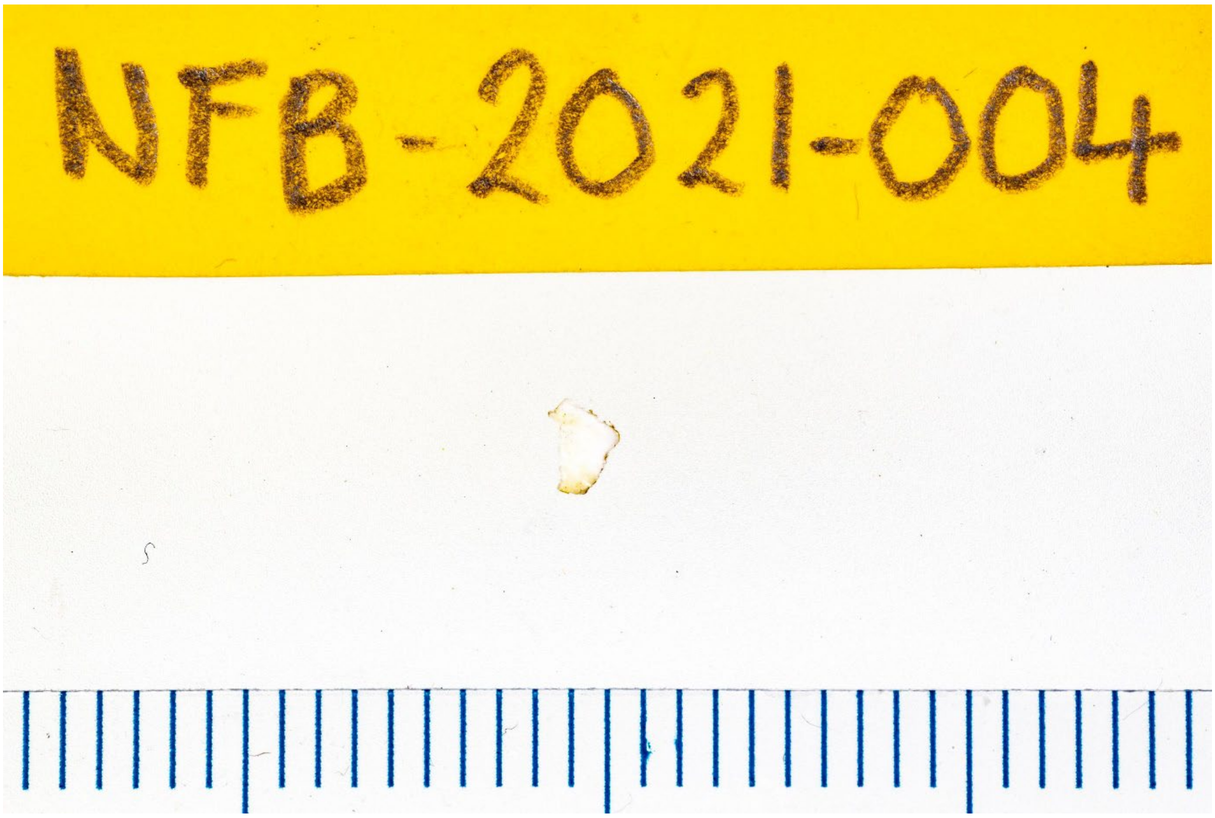
* MESSAGE: s.e.s are based on dispersion parameter with value 1.

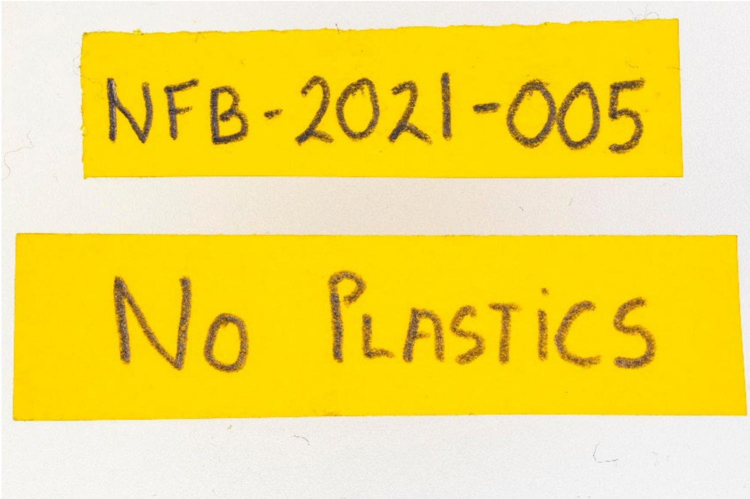
Photos of Newfoundland Banks Fulmar stomach samples

Photos show the plastic samples with at the top the yellow label with the NFB sample number, and along the bottom a mm scale to illustrate the particle sizes. Virtually all particles were recovered from the muscular gizzards, with only a few from the large proventriculus in 4 birds. Where relevant, a small note is given below the photo, for example on the stomach part from which the particles were recovered. Stomach details can also be recovered from the information in Table S1. Some discrepancies may seem to exist between numerical details in Table S1 and the photos shown below. Photos were taken after FTIR analyses. Some items were cut, or scraped along the surface in order to provide a clear surface for the FTIR measurement. Pressure in the FTIR machine on particles caused fragmentation of some particles.

NFB-2021-002: greenish threads at left of photo were found in the proventriculus.


NFB-2021-003


NFB-2021-004

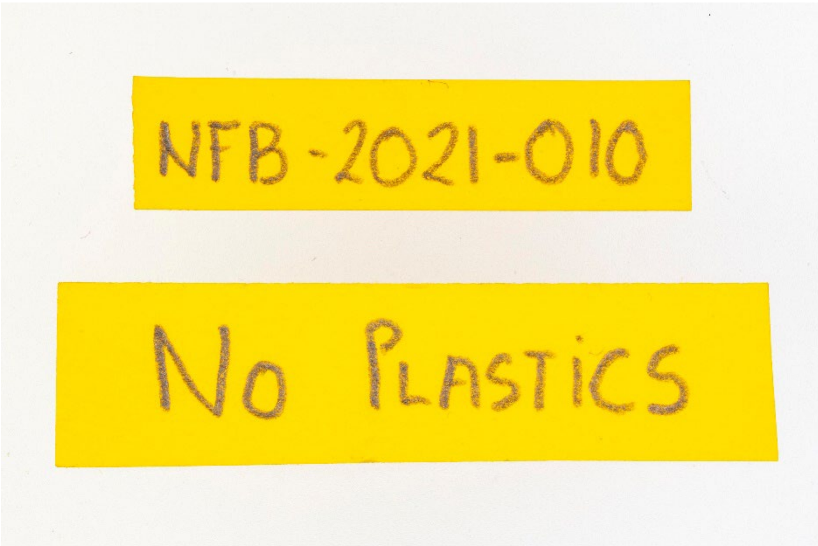

NFB-2021-005
No Plastics


NFB-2021-006


NFB-2021-007


NFB-2021-008

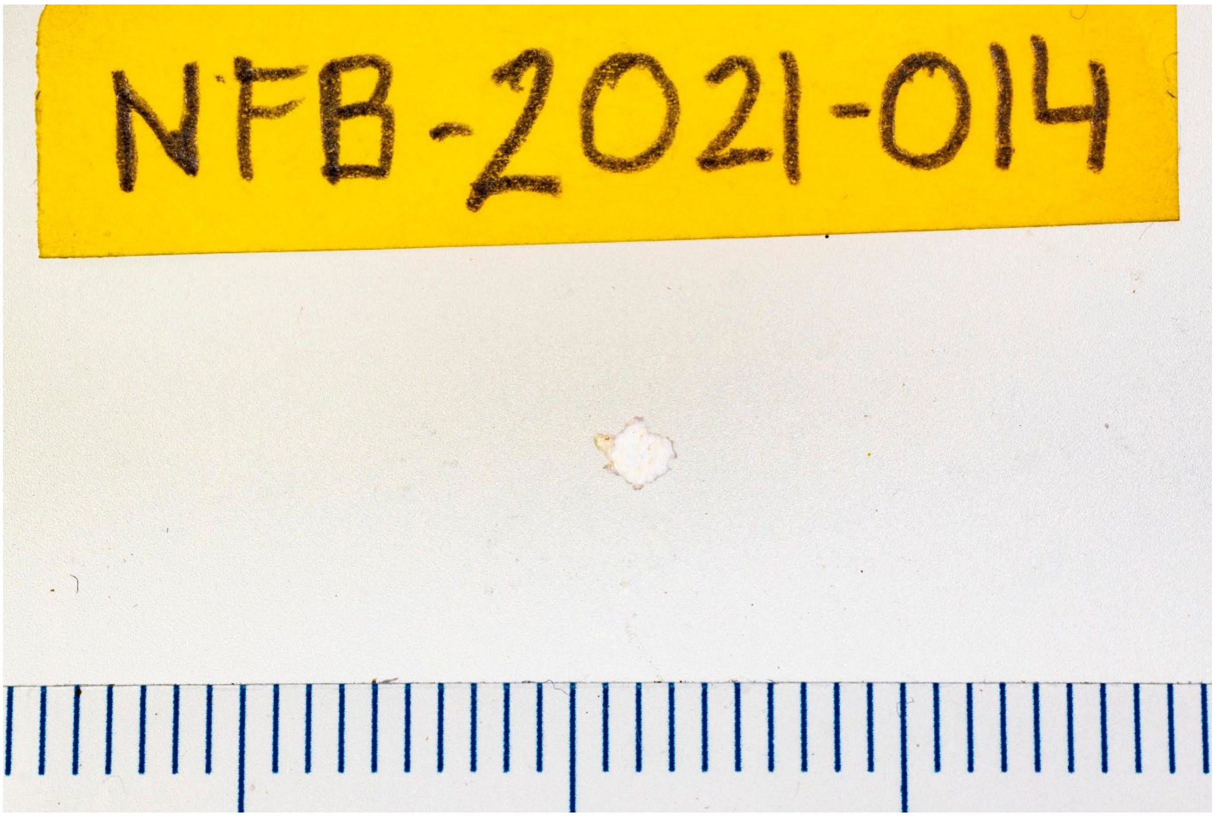

NFB-2021-009

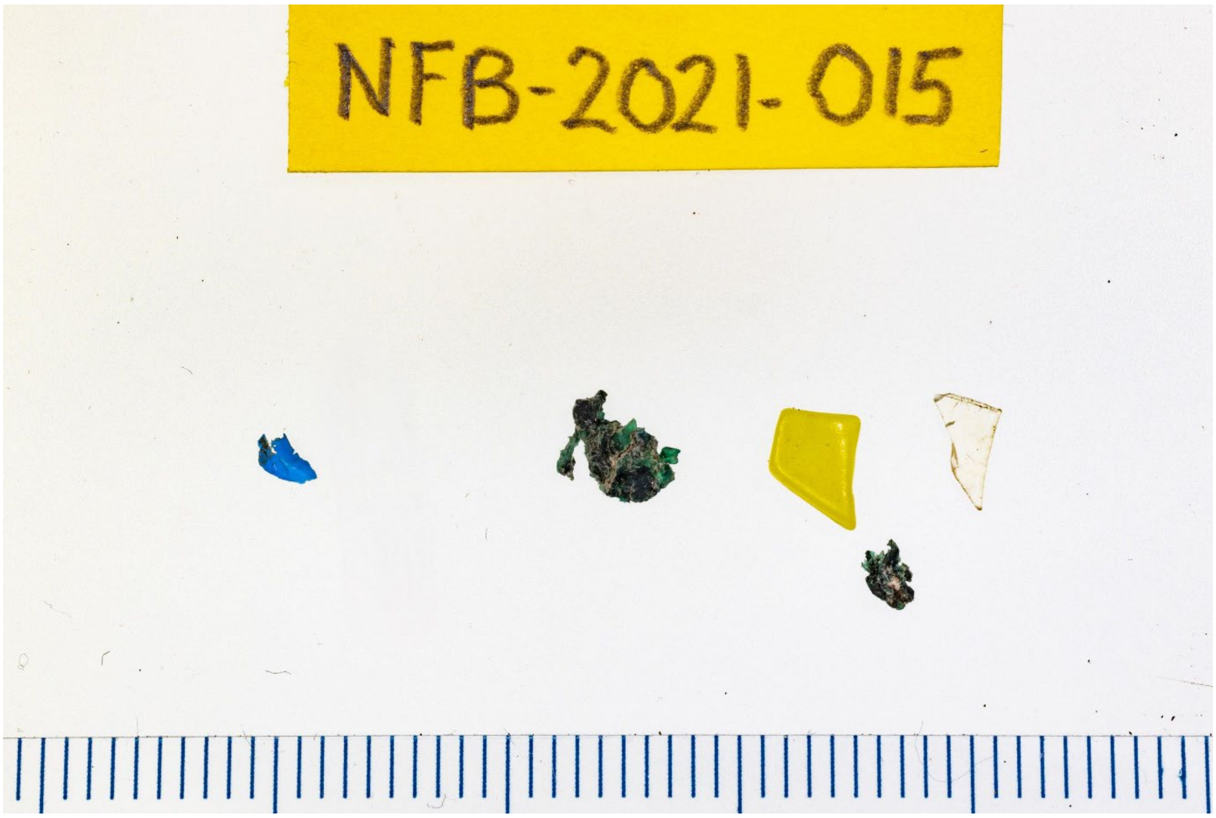

NFB-2021-010
No Plastics


NFB-2021-011

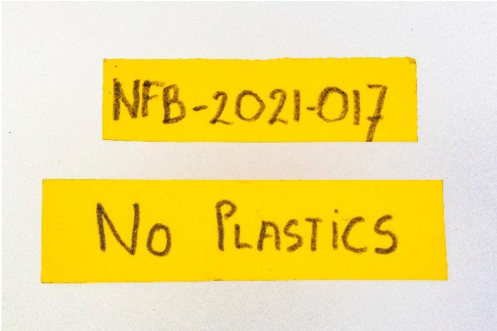

NFB-2021-012

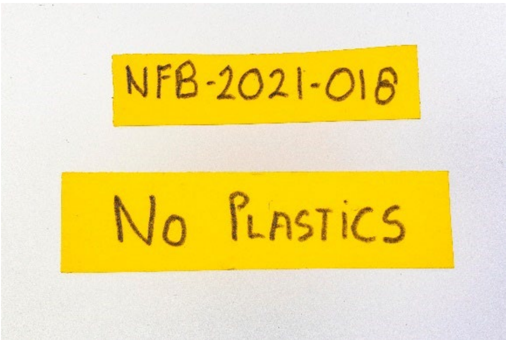
NFB -2021-013 The large bundle at the right was not included as plastic because considered to be wool hairs consolidated into a ball in the grinding gizzard.

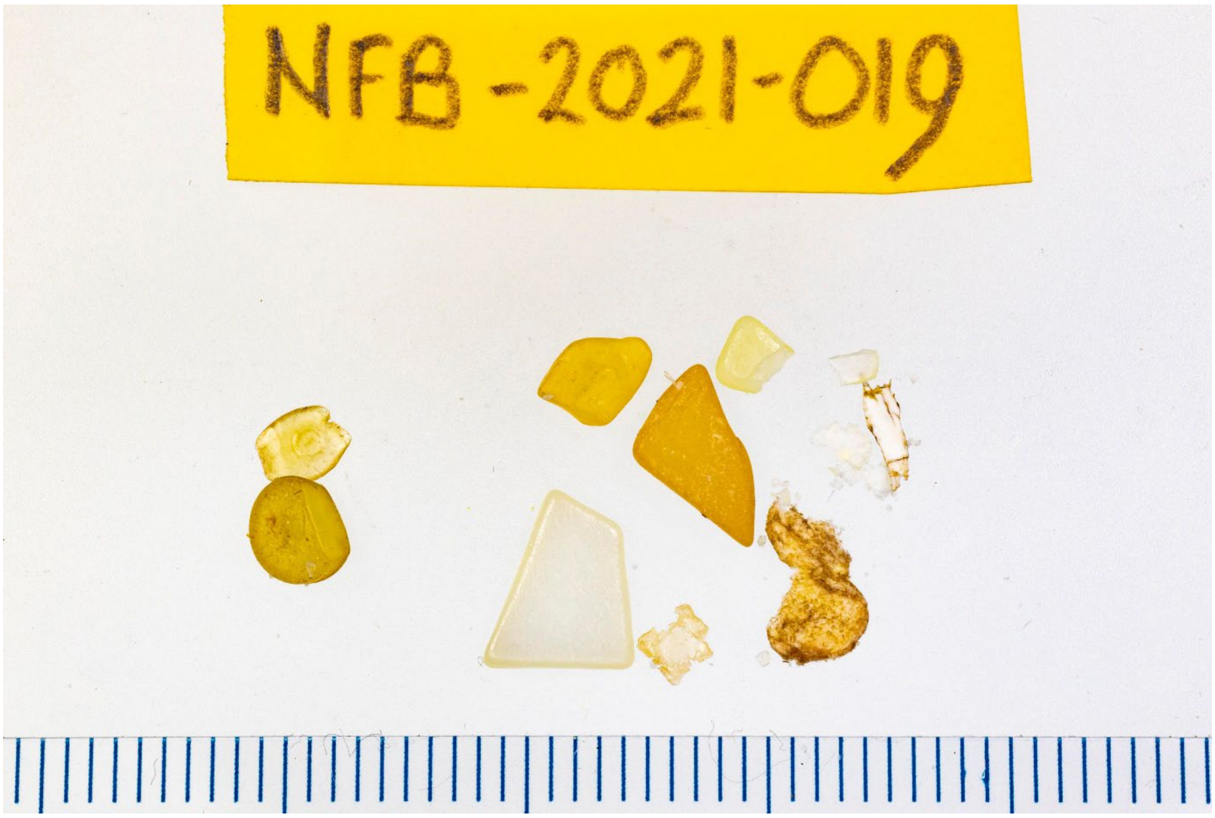


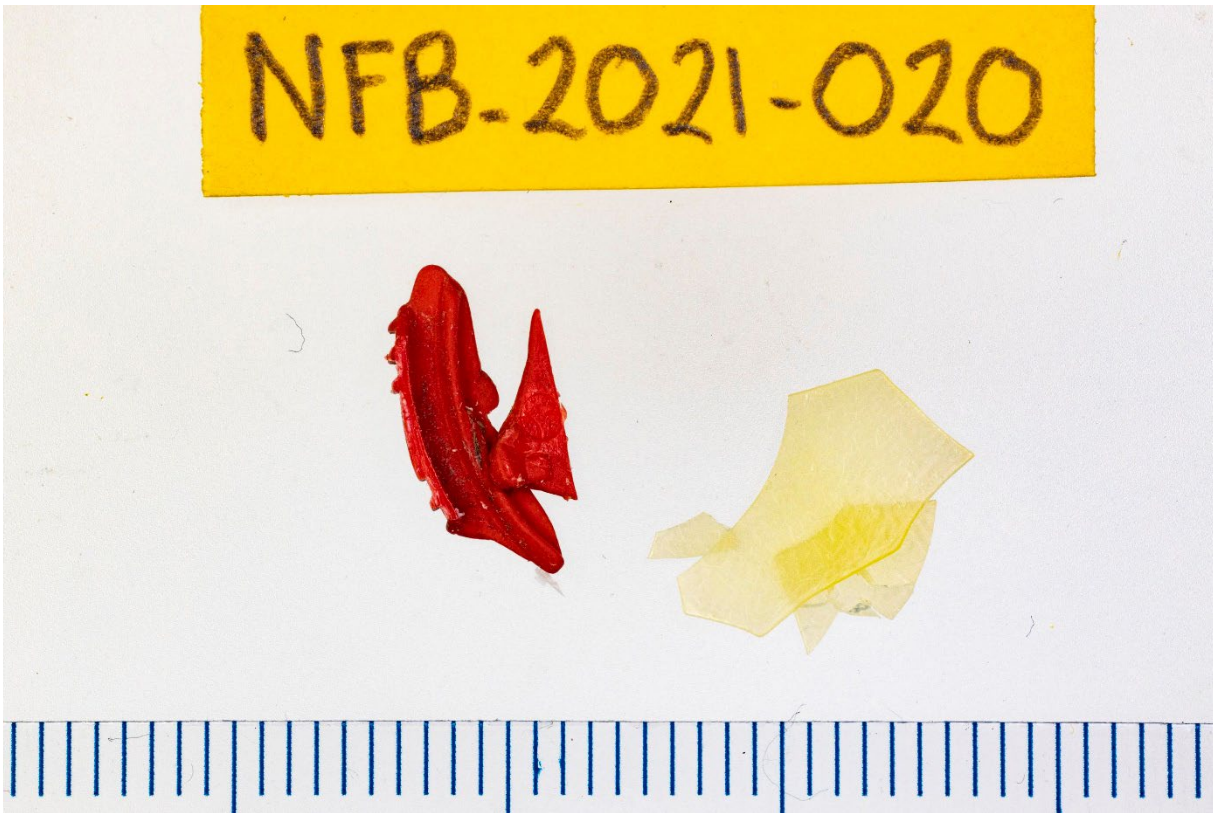


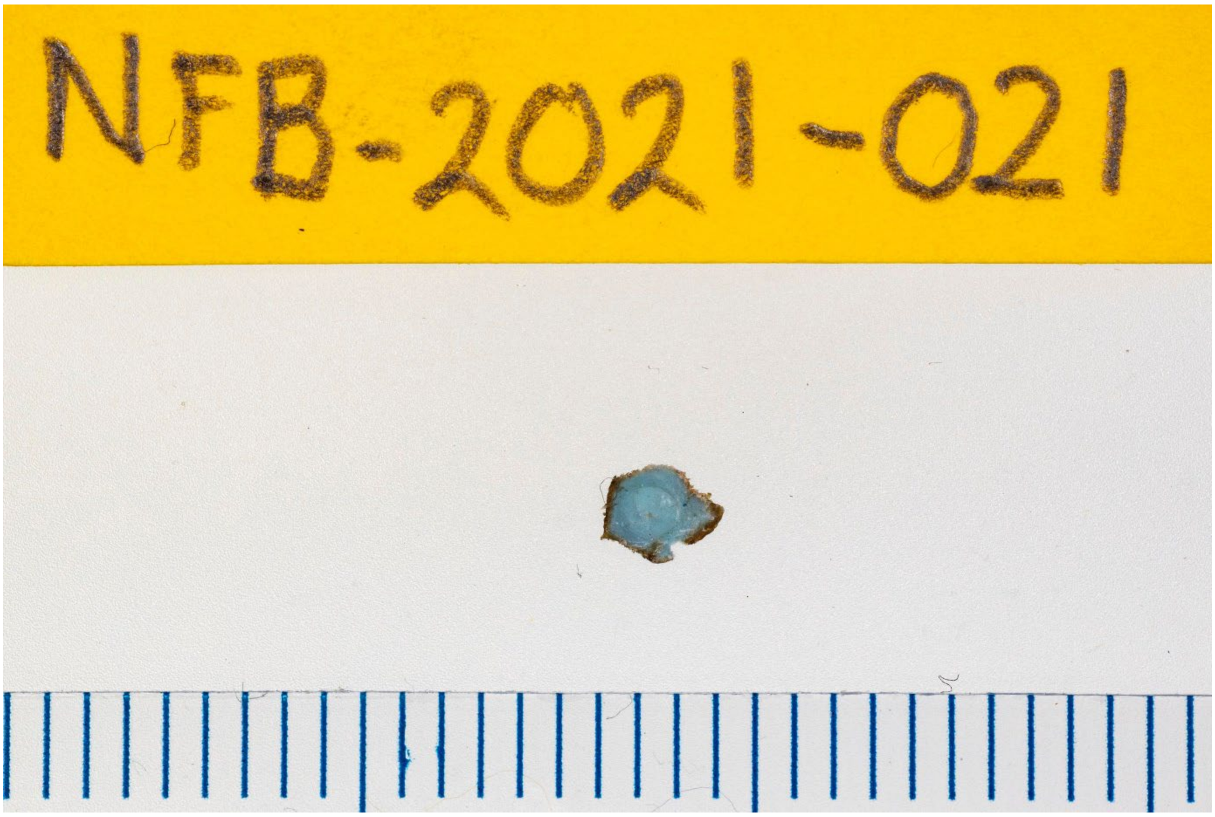
NFB 2021-015: The blue particle at the left was found in the proventriculus.


NFB-2021-017
No Plastics

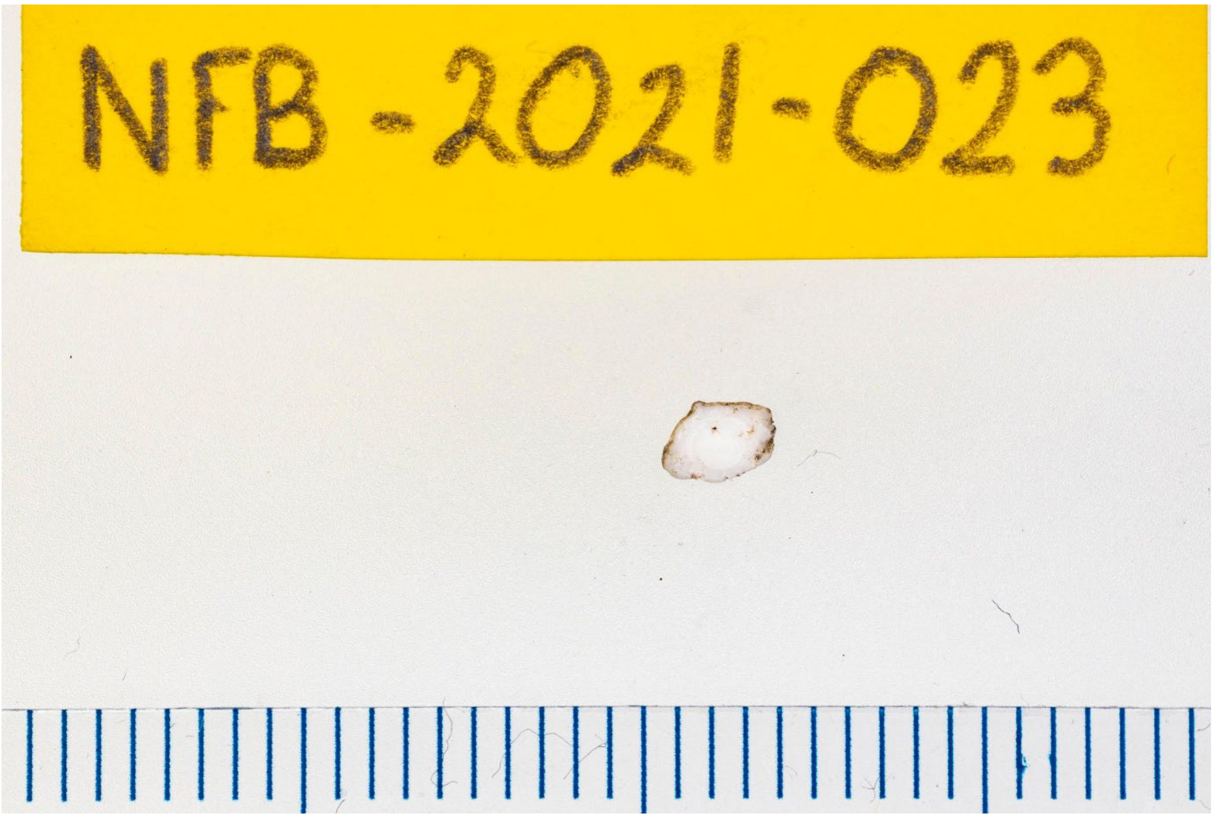

NFB-2021-018
No Plastics


NFB-2021-019


NFB-2021-020


NFB-2021-021


NFB-2021-022


NFB-2021-023

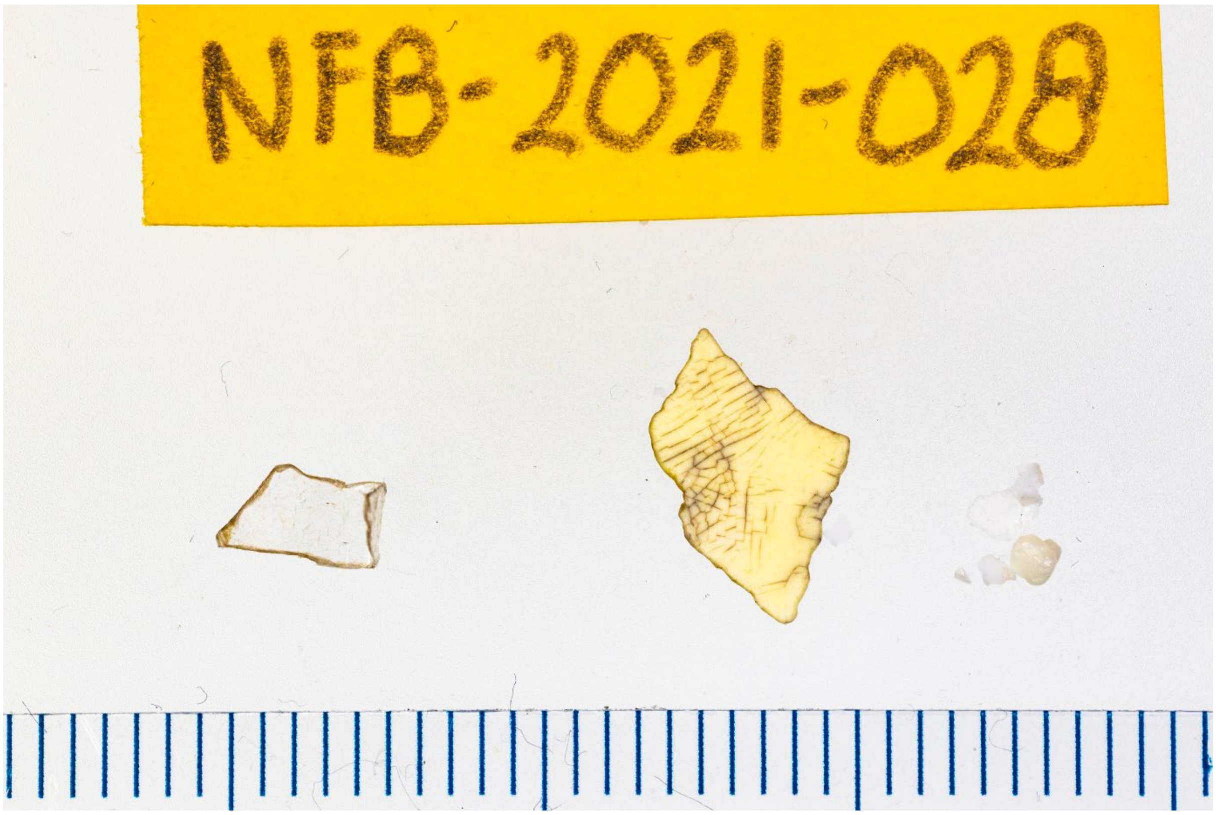

NFB-2021-024

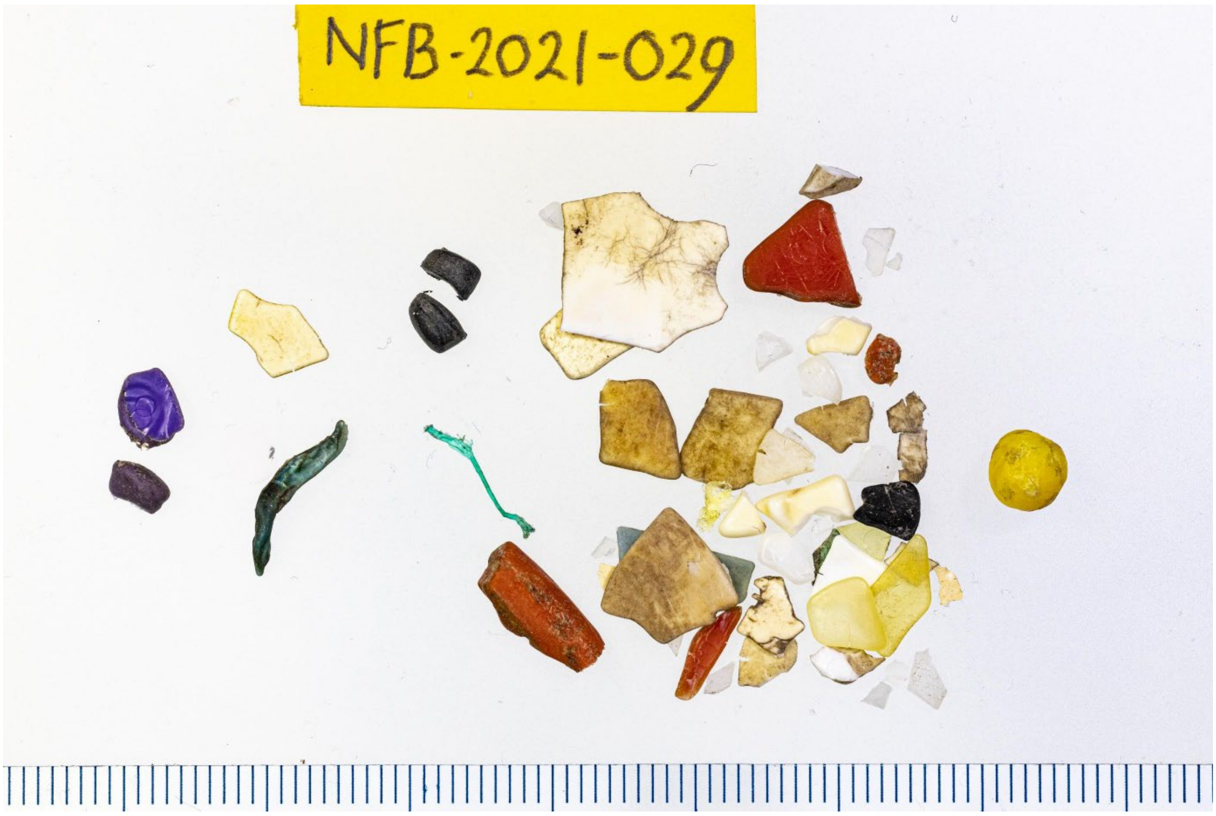

NFB-2021-025


NFB-2021-026

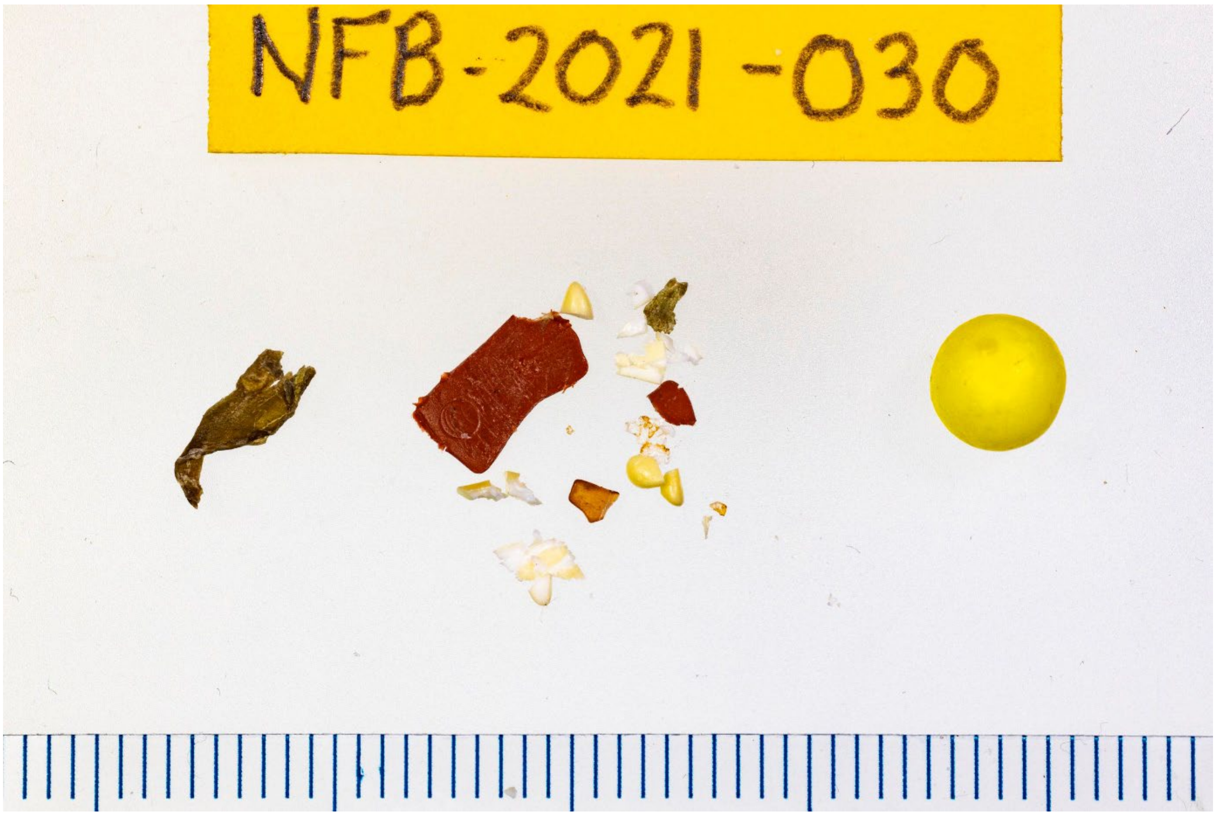

NFB-2021-027

NFB-2021-029: The four particles at the left were found in the proventriculus.





NFB-2021-029: The four particles at the left were found in the proventriculus.



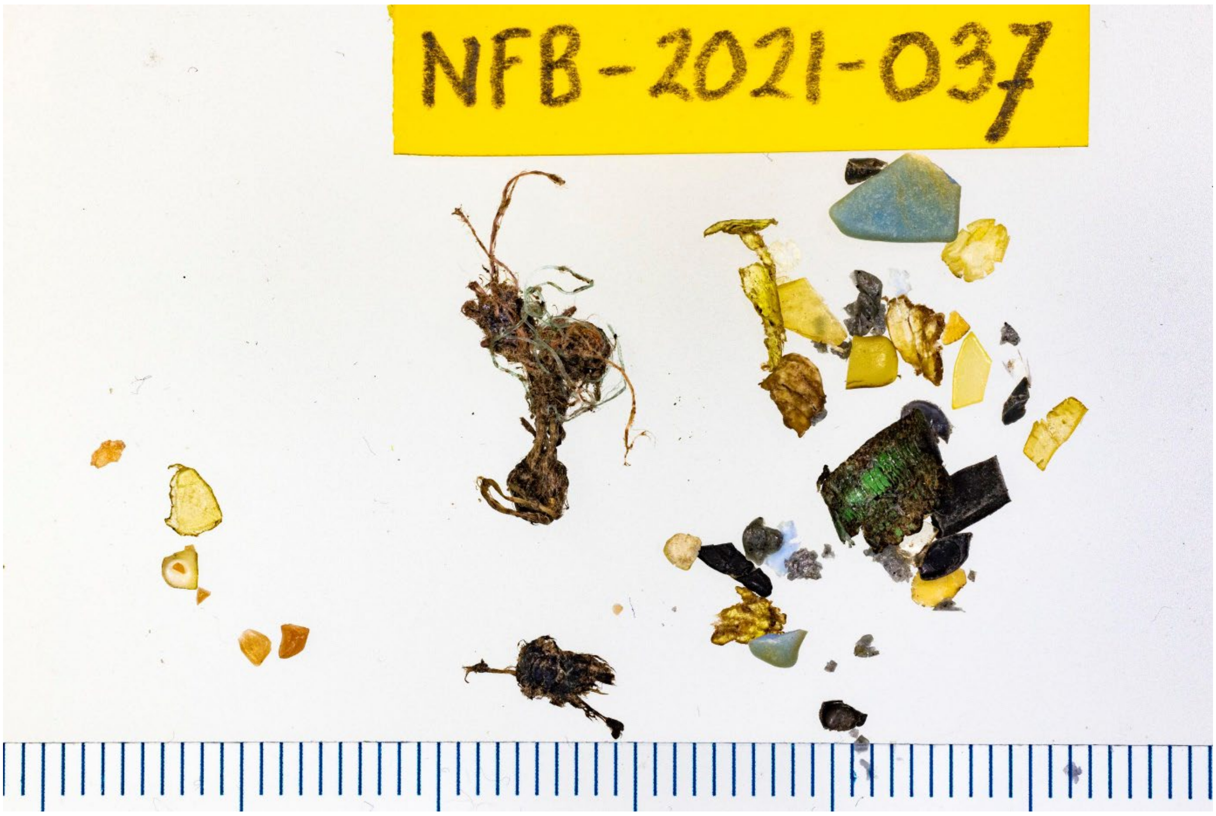
NFB-2021-030: The yellow ball at the right is a soft-airgun bullet.

NFB-2021-031: The orange ball is a soft-airgun bullet, with some scraped off material to the side.

NFB-2021-032: The large object at the right is a thin flat sheetlike particle.


NFB-2021-034


NFB-2021-035



NFB-2021-037: The particles at the lower left are (partly broken) bits of three fragment in the proventriculus. All other items come from the gizzard.

Highlights

- 89 % of Newfoundland Banks fulmars ingested plastic, on average 6.6 items, 0.093 g.
- 27 % exceeded the FTV (Fulmar Threshold Value) of >0.1 g ingested plastic.
- The FTV% was much lower than expected at this latitude.
- Plastic ingestion correlated strongly to sea surface temperatures.
- Sea surface temperatures reflect the effects of ocean currents.

Graphical Abstract