Marine Pollution Bulletin 202 (2024) 116365

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Life starts with plastic: High occurrence of plastic pieces in fledglings of northern fulmars

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ARTICLE INFO

Keywords:
Microplastics
Fulmarus glacialis
Particle size
Early life stages
FTIR
Arctic

ABSTRACT

Plastic pollution threatens many organisms around the world. In particular, the northern fulmar, *Fulmarus glacialis*, is known to ingest high quantities of plastics. Since data are sparse in the Eurasian Arctic, we investigated plastic burdens in the stomachs of fulmar fledglings from Kongsfjorden, Svalbard. Fifteen birds were collected and only particles larger than 1 mm were extracted, characterised and analysed with Fourier Transform InfraRed spectroscopy. All birds ingested plastic. In total, 683 plastic particles were found, with an average of 46 ± 40 SD items per bird. The most common shape, colour and polymer were hard fragment, white, and polyethylene, respectively. Microplastics (< 5 mm) were slightly more represented than mesoplastics (> 5 mm). This study confirms high numbers of ingested plastics in fulmar fledglings from Svalbard and suggests that fulmar fledglings may be suitable for temporal monitoring of plastic pollution, avoiding potential biases caused by age composition or breeding state.

1. Introduction

Plastic pollutes the world including pristine regions, such as the Arctic (e.g. Bergmann et al., 2022; Halsband and Herzke, 2019). For instance, Arctic organisms interact with plastic through ingestion and all groups of marine fauna are impacted (Collard and Ask, 2021). The northern fulmar *Fulmarus glacialis*, hereafter called fulmar, is known to ingest plastics and has been used a bioindicator of plastics in the North Sea region since 2002 (OSPAR Commission, 2008). Its feeding strategy (i.e. opportunistic) and its physiology (i.e. gut morphology) have been suggested as reasons for high plastic ingestion (van Franeker et al., 2011; Furness, 1985). Because of these high ingestion rates, the retention time of plastic particles is important and can lead to possible biological impacts such as reduction of available gut volume and gut obstruction, leading to loss of weight and poor body condition (e.g. Wilcox et al., 2015; Nania and Shugart, 2021).

Fulmars are now part of a defined biomonitoring program in two regions: the North Sea (OSPAR Commission, 2008; van Franeker et al., 2011) and Iceland (Snæþórsson, 2021). The Convention for the Protection of the Marine Environment of the North-East Atlantic (Oslo-Paris Convention, OSPAR) have defined specific guidelines on the collection of samples, the extraction of plastic pieces from fulmar stomachs, and the expression of the results (OSPAR Commission, 2008; OSPAR, 2010). The OSPAR Convention also proposes an ecological quality objective (EcoQO) as follows: "*There should be less than 10% of northern fulmars (Fulmarus glacialis) having more than 0.1 g of plastic particles in the stomach of 50–100 beach-washed fulmars from each of 4–5 areas of the North Sea over a period of at least five years*" (OSPAR Commission, 2008). The Arctic Monitoring and Assessment Programme (AMAP) have recently defined the fulmar as a Priority 1 recommendation for monitoring (Arctic Monitoring and Assessment Programme (AMAP), 2021). Consequently, the fulmar has been studied across many regions of the world, including the Arctic. However, age composition and sampling season are increasingly considered as potential factors undermining comparability among these incidental studies with small sample sizes (Collard et al., 2022a; Trevail et al., 2015; Tulatz et al., 2023; van Franeker, 1985).

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https://doi.org/10.1016/j.marpolbul.2024.116365
Received 31 May 2023; Received in revised form 5 April 2024; Accepted 7 April 2024
Available online 11 April 2024

Fledglings are a specific age class of young birds which have left the nest (around 50–53 days old (Mallory et al., 2020)) and start to feed themselves at sea. During those few days, the fledglings are flightless due to their weight which can reach up to 115 % of an average adult weight (Mallory et al., 2020) as well as their premature enzyme system which is not yet fully developed (Bishop et al., 1995). Fledglings are thus an easy candidate for biomonitoring as they are easy to catch during that short period of time. Also, the ingested plastics come from the parents and represent a specific foraging area, unless large pieces are stuck in the first part of the stomach, the proventriculus, from before the breeding season. Finally, since plastic burdens in fulmars are influenced by the seasons (Mallory, 2008; Tulatz et al., 2023; van Franeker et al., 2022), this bias impairing comparability is therefore avoided as fledglings are only found at a specific time of year.

Arctic seabirds undergo multiple stressors, including climate change and chemical pollution. The western coast of the Svalbard archipelago is of particular interest because of the influence of the West Spitsbergen Current. This current brings warm Atlantic waters (Polyakov et al., 2005) to the northwest of Svalbard, and to several fjords, including Kongsfjorden. Kongsfjorden transitions from an ice-covered Arctic fjord in winter, towards an Atlantic ice-free fjord in summer months (“Atlantification”, Hop et al., 2002; Hegseth and Sundfjord, 2008; De Rovere et al., 2022). These changes in water masses will cause responses in organisms living in this region, including seabirds. An atlantification of Kongsfjorden will lead to a depletion in sea ice cover and progressive disappearance of glaciers, causing a decrease in large, lipid-rich preys that seabirds prey on (Hop et al., 2002). In the case of the fulmar, because of its opportunistic feeding strategy, this change in water masses could lead to a higher ingestion of plastic, making the colonies on the western coast of Svalbard possibly more exposed to plastics.

In this baseline study, our objective was to quantify plastic burdens in fulmar fledglings from Kongsfjorden in order to confirm the high numbers previously observed by Tulatz et al. (2023). We aimed to provide more insight towards the possible use of fulmar fledglings for biomonitoring of plastic pollution. More data are needed to confirm the high levels before biomonitoring can be recommended.

2. Methods

2.1. Sampling

In September 2021, 15 fulmar fledglings were collected with a D-shaped landing net at sea in Kongsfjorden, Svalbard (78°55′N, 11°56′E). Fledglings were sacrificed with cervical dislocation. This study is part of a project registered in ‘Research in Svalbard’ (RiS ID: 11750). The birds were frozen at −20 °C and sent to Tromsø, Norway, for further dissections.

The birds were dissected according to standardized protocols (OSPAR Commission, 2015; van Franeker, 2004) adapted for the needs of this study. Birds were sexed, weighed and measurements of tarsus, wing, gonys, and both head and bill together were taken (Table S1). All birds were fledglings and therefore around 50 to 60 days old. Both the proventriculus and the gizzard were scrutinized for lesions or punctures during dissection but could not be evidenced. In a break from protocol, the Bursa of Fabricius aspect was not reported.

2.2. Plastic extraction

Plastic extraction was performed according to Collard et al. (2022a) except that both the proventriculus and gizzard, hereafter called ‘stomach’, of each bird were extracted, and pooled in the same glass beaker. A 10 % KOH solution was added with a volume ratio of 1:3 (tissue:KOH) (Rochman et al., 2015). The beakers were then put on a shaker (IKA HS 501 digital, Staufen, Germany) at 100 rpm. After two days, the solutions were sieved through a 1-mm mesh size and a 20-μm mesh size stainless steel sieves. The retained particles were rinsed off with milliQ water and transferred into a filtration unit for vacuum filtration, equipped with a 5-μm cellulose acetate filter membrane. Only particles larger than 1 mm (OSPAR Commission, 2008) were analysed by spectroscopy and included in this study. Even though the OSPAR protocol for the extraction of plastics from stomach content does not include chemical digestion such as with KOH, we believe our results are directly comparable to OSPAR studies. The use of a digestive agent was preferred to ease the spectroscopic analyses and to make the plastic pieces more visible.

2.3. Characterization of the plastic particles

The plastic particles were sorted using the ‘Save the North Sea’ protocol into industrial (pellet) and user plastic (fragment, thread, sheet, foamed (van Franeker et al., 2005)). The particle lengths were determined by placing them on a millimetre-gridded paper and photographed (smartphone Samsung Galaxy A51, Seoul, South Korea) before their identification by FTIR. The photographs were then imported into the Image J v1.52 software and measurements were taken. As recommended by Hartmann et al. (2019), only the largest dimension was measured. As recommended by Provencher et al. (2017), plastics were categorized into one of the eight colour groups: off/white–clear; grey–silver; black; blue–purple; green; orange–brown; red–pink, or yellow. Light-coloured plastic was defined as off/white, yellow and orange-brown categories. The plastic particles were weighed per polymer and individual (Quintix64-1S, Sartorius AG, Göttingen, Germany).

2.4. FTIR spectroscopy

All extracted particles were identified using the Fourier Transform Infrared (FTIR) Spectrometry technique (infrared spectrometer Cary 630 with Diamond Attenuated total reflectance (ATR), Agilent technology, Santa Clara, US) and a hit quality index (HQI) superior or equal to 0.7 was required for a particle to be assigned a polymer. The windows for detection of spectra were set between 4000 and 650 cm^{-1} and the resolution was set at 8 cm^{-1}. Between each particle analysis, the diamond crystal was cleaned, and scans were collected to adjust for background noise. The obtained spectra were compared to a modified ATR Demo reference library at the Norwegian Institute for Air Research (NILU) in Tromsø. If a satisfying match could not be obtained, the particle was scratched with a scalpel or sliced, and its spectrum was determined a second time. If the second match did not reach a HQI of 0.7, the particle was classified as “Undetermined”.

2.5. Quality assurance and quality control

Similarly to Collard et al. (2022b), our study was limited to particles larger than 1 mm which are less prone to originate from the contamination of the working environment. However, we did our utmost to prevent contamination as our samples might be investigated for smaller particles (<1 mm) in the future. Therefore, each step, from the dissection of the birds to the selection of particles for identification, was performed to prevent any microplastic cross-contamination: a cotton lab coat and gloves were worn, beakers were covered when not manipulated, plastic materials were avoided as much as possible (gloves and tubes for storage after plastic extraction were made of plastic), the KOH solution was filtered through the same filter membrane than mentioned earlier and all laboratory equipment was rinsed with filtered milliQ water before and after use. To reduce airborne contamination, all laboratory work was performed under a fume hood. Blanks were run for potential further investigation of smaller MPs, but were not included in this study as no particle larger than 1 mm was found in those blanks. All the filter membranes, including blanks, were retained for future studies of smaller microplastic particles.

2.6. Ethical statement

The fledglings were sampled in Svalbard, after approval by the Governor of Svalbard under the permit nr. 21/01412–2. In Svalbard, it is very challenging to collect beached fulmars as there are few beaches, and they are remote and hard to access. Besides, the presence of top predators such as the polar bear and the Arctic fox would prevent a collection of dead birds in good shape with intact digestive systems. This study aimed at investigating plastic burdens in fledglings, a specific age class of fulmars. Therefore, an opportunistic sampling on beaches could not have provided enough fledgling carcasses for study. We sampled 15 individuals as a compromise between the number of samples and the potential impact on the fulmar population. The sacrifice of birds was performed by cervical dislocation by skilled and experienced staff immediately onboard to diminish as much as possible stress and pain. The birds' digestive tracts were used for this study, and other tissue were also collected to maximize the sampling. These will be utilised for other investigations.

3. Results

All fifteen fledglings contained ingested plastic (Fig. 1), with a median of 35 particles per bird (mean 46.0 ± 39.6 SD, quartiles 18.5–53.5, range: 8–139, Table 1). The total mass of ingested plastics was 4.67 g with an average of 0.31 g (± 0.24 SD) per bird. Twelve birds (80 %) were above the EcoQO of 0.1 g of plastic in the stomach. Among the total of 683 pieces of plastic, only 14 were industrial plastics (or pellets). The most common polymers were polyethylene (PE) and polypropylene (PP), representing 65 % and 27 %, in numbers of all polymers, respectively. The other polymers found were polystyrene, polyamide, acrylonitrile butadiene styrene, polyethylene terephthalate and polyurethane. Off/white and yellow particles were the dominating colours of ingested particles (45 % and 32 %, respectively). Light coloured plastics represented 82 % of all the plastics found. Most plastics were hard fragment (83 %). Seven of the 15 fledglings regurgitated at sea upon capture, leading to a possible underestimation of the plastic burden in their stomachs.

All the fledglings were in very good body condition, with a body mass varying from 830 g to 1120 g. No correlation between body mass and both the plastic count and plastic mass could be evidenced.

4. Discussion

The northern fulmar is the only bioindicator of plastic pollution and has therefore been extensively studied compared to other seabird species, within and outside of the Arctic (Baak et al., 2020; Collard and Ask, 2021). All previous studies conducted in Svalbard showed high frequencies of occurrence (Collard et al., 2022a; Trevail et al., 2015; Tulatz et al., 2023; van Franeker, 1985). The high burdens of plastics in fulmar fledgling stomachs are similar to another recent study whereby fledglings collected in 2020 had an average of 0.34 g ± 0.08 SE of plastic per stomach. Each fledgling had ingested at least one plastic piece (Tulatz et al., 2023). Our study is in accordance with these results. It is noteworthy that our study analysed the plastic burden in 15 individuals only. That number of samples might not be perfectly representative of the population but shows however that fledglings do ingest remarkable numbers of plastic pieces overall. Besides, a low number of sampled individuals prevent an extended data analysis, such as comparison between sexes, which could not be performed here.

Variations of plastic burdens between young and older seabirds can be explained by several factors such as the experience in selecting prey, the time spent on land and the parental transfer (Skórka and Wójcik, 2008; van Franeker, 2012; van Franeker et al., 2022). The chicks leave the nest when the parents stop feeding them and start looking for their own food. That lack of experience combined with a strong feeling of hunger could lead to a more opportunistic feeding behaviour resulting in a higher level of plastic pieces in their stomachs compared to levels in adults. Bond et al. (2021) and van Franeker et al. (2022) also suggested that older birds which spend more time at the colony, could get rid of ingested plastic. Fulmars can spit plastics along with oil as a defence mechanism against predators while, males also spit during nest-site disputes (van Franeker et al., 2022). Adults also empty their stomachs while feeding their chicks, resulting in parental transfer of plastic pieces. Our fledglings were collected right after the chick-rearing season, in which they are fed by the parents exclusively. The fledglings were caught at sea, still unable to fly, meaning that the time spent out of the

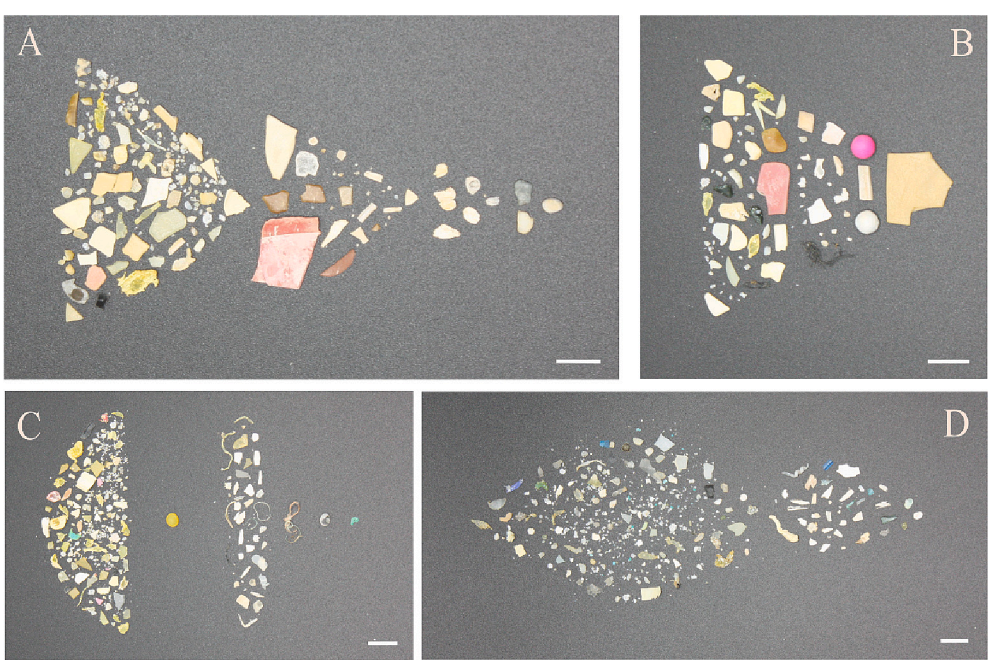

Fig. 1. Examples of all the plastics found in four fulmar fledglings, including the three with the highest numbers of plastics. A: F01-21Sv, B: F05-21Sv, C: F10-21Sv, D: F13-21Sv. Scale bars: 1 cm.

Table 1
Overview of the levels and characteristics of the plastics ingested by the fulmar fledglings. PE: polyethylene, PP: polypropylene.

Bird ID	Number of user plastics	Mass of user plastics (g)	Number of pellets	Mass of pellets (g)	Dominant polymer	Dominant shape	Dominant colour	Total number	Total mass (g)
F01-21Sv	71	0.547	4	0.053	PE	Hard fragment	Yellow	75	0.600
F02-21Sv	27	0.147	1	0.024	PE	Hard fragment	White	28	0.171
F03-21Sv	19	0.172	0	0	PE	Hard fragment	Yellow	19	0.172
F04-21Sv	63	0.597	0	0	PE & PP	Hard fragment	White	63	0.597
F05-21Sv	39	0.868	0	0	PE	Hard fragment	White	39	0.868
F06-21Sv	41	0.495	3	0.062	PE	Hard fragment	White	44	0.557
F07-21Sv	17	0.052	1	0.026	PE	Hard fragment	White	18	0.078
F08-21Sv	34	0.270	1	0.019	PE	Hard fragment	White	35	0.289
F09-21Sv	8	0.048	0	0	PP	Hard fragment	White	8	0.048
F10-21Sv	129	0.374	2	0.049	PE	Hard fragment	Yellow	131	0.423
F11-21Sv	8	0.113	1	0.020	PE	Hard fragment	Yellow	9	0.133
F12-21Sv	37	0.135	0	0	PE	Hard fragment	White	37	0.135
F13-21Sv	138	0.356	1	0.009	PE	Hard fragment	White	139	0.365
F14-21Sv	11	0.037	0	0	PE	Hard fragment	White	11	0.037
F15-21Sv	27	0.196	0	0	PE	Hard fragment	Yellow	27	0.196
Total	669	4.407	14	0.262	–	–	–	683	4.669

The size range of all plastics was from 1.0 mm to 106.2 mm, with an average of 5.6 mm (± 5.5 SD) and a median of 4.7 mm (1st quartile: 3.3 mm, 3rd quartile: 6.5 mm). A bare majority of the plastics were microplastics (< 5 mm, 56 %).

nesting area was very short -a matter of days- and highly unlikely to have led to a significant ingestion of plastic pieces. Even though the nest area could also be a potential source of plastic (J. Danielsen, pers. comm.), the nest does not constitute a source of plastics. Indeed, as fulmars breed on narrow ledges and do not build nests, it is impossible that unfledged fulmar chicks have access to plastic pollution other than by parental transfer. All those parameters lead to high ingestion rates of plastics by fledglings. Yet, the importance of those factors is unknown and the fate and impacts of those plastics on first-year fulmars is poorly understood.

Investigations of plastic ingestion by chicks of procellariiform seabirds already existed back in the 1960s where already high masses and/or high frequencies of occurrence were reported in different species (Kenyon and Kridler, 1969; Auman et al., 1998; Lavers and Bond, 2023; Youngren et al., 2018). Despite a growing interest for plastic ingestion by fledglings in the European Arctic (Amélineau et al., 2016; Ask et al., 2020; Tanaka et al., 2019; van Franeker, 2012), plastic ingestion by chicks on Svalbard has been only recently studied and only in fulmar chicks or fledglings (Collard et al., 2022b; Tulatz et al., 2023). These few studies show that even in the remote Arctic, seabird chicks are fed plastic, mostly fragments, with frequencies of occurrence above 90 %. While our study focuses on a seabird species that has been greatly investigated for plastic pollution, it adds evidence to support the importance of the fulmar for future monitoring.

Most of the ingested plastic in our study were light coloured, a result common to many previous studies on plastic ingestion by seabirds (Amélineau et al., 2016; Collard et al., 2022b; Robards et al., 1995; Santos et al., 2016; Verlis et al., 2013; Vlietstra and Parga, 2002). Before ingesting a prey - or a plastic piece - animals need to encounter it and see it. Animals feeding from above the sea will more easily see light coloured prey or particles as the water column appears dark (Thayer, 1896), when deep enough. Similarly, considering particles of the same size, fragments will be more evident than fibres. The fulmar flies above the sea surface to spot their prey before picking them. Finding more light-coloured, hard fragment, plastic than dark plastic is therefore consistent with Thayer's law (Santos et al., 2016; Thayer, 1896) even though fibres and dark coloured particles are the most common microplastics in Arctic surface waters (e.g. Carlsson et al., 2021; Jiang et al., 2020; Liboiron et al., 2021; Lusher et al., 2015). Beside the colour, there is also a pattern in the shape of the ingested plastics. Hard fragments are the dominant plastic shape commonly ingested by fulmars (e.g. Collard et al., 2022a; Kühn et al., 2021; Sühring et al., 2022; Tulatz et al., 2023; van Franeker et al., 2022). This means that floating secondary micro- or mesoplastics, i.e. plastic pieces resulting from the fragmentation of larger plastic debris, constitute the main source of plastic ingested by fulmars over primary micro- or mesoplastics.

One priority question remaining to be answered relates to the impacts of plastic ingestion. Both toxicological and physical impacts are expected but more evidence is needed. Some studies reported tissue puncturing (Tulatz et al., 2023) and other tissue damage such as collagenous thickening or disorganisation of the proventriculus submucosa and fibrosis (Charlton-Howard et al., 2023; Rivers-Auty et al., 2023). Even though uncommonly observed, mechanical impacts do occur. The impacts of plastic ingestion can therefore have deleterious impacts on the individual level but the consequences on the population level constitute a large knowledge gap (Browne et al., 2015; Werner et al., 2016). Plastic ingestion is another factor impacting seabirds at the individual, and perhaps at the population level, supporting the need for monitoring programmes and further studies on early life stages.

Similar to more populated regions, Svalbard seems to be a place where fulmars, of all age classes, ingest a lot of plastic and is therefore worth considering in the possible frame of monitoring in the Arctic. Our study is indeed not the first one performed in Svalbard that shows high occurrence and burdens of plastic in fulmar (Tulatz et al., 2023; Trevail et al., 2015; Collard et al., 2022a). It however supports the inclusion of Svalbard of a potential biomonitoring programme. Besides, given the high burdens in fulmars from Svalbard the impacts of such ingestion should be investigated. A few recently published studies showed some of the adverse effects on seabirds' health, including fibrosis and loss of tissue structure (Charlton-Howard et al., 2023; Fackelmann et al., 2023; Fackelmann and Sommer, 2019; Rivers-Auty et al., 2023). These studies present new perspectives in scientific research, and the fulmar populations from Svalbard are likely to be a candidate for such impact studies, as well as for biomonitoring purposes. Fledglings as a homogenous age group are also a good source for further studies on plastic related contaminants, avoiding sex- and breeding status related confounders. We want to encourage future studies to investigate the suitability of non-lethal methods such as imaging or blood sampling for plastic-related chemical quantification as those methods could hopefully then be used for biomonitoring over the killing and dissection of those birds. In that perspective, fulmar fledglings are also a good candidate as they can be caught easily alive at sea, allowing scanning and blood sampling. Fulmar fledglings would be suitable for temporal monitoring of marine plastic pollution in Svalbard, scalable to regional monitoring across the Arctic, including regions were fulmar fledglings are harvested for consumption - with the avoidance of killing birds only for science by cooperating with hunters. By this approach it would be possible to avoid age composition and sampling season as a bias source for inter-study comparability.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116365.

CRediT authorship contribution statement

France Collard: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Stine C. Benjaminsen:** Writing – review & editing, Investigation. **Dorte Herzke:** Writing – review & editing, Resources. **Eirin Husabø:** Writing – review & editing, Investigation. **Kjetil Sagerup:** Writing – review & editing, Supervision. **Felix Tulatz:** Writing – review & editing, Investigation. **Geir W. Gabrielsen:** Writing – review & editing, Supervision, Resources, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

France Collard reports financial support was provided by the Fram Centre and the Research Council of Norway. Dorte Herzke reports financial support was provided by the Research Council of Norway.

Data availability

Data will be made available on request.

Acknowledgements

The authors want to thank the staff at the Sverdrup station, Ny-Ålesund. This study was funded by the Fram Centre Research Programme "Plastic in the Arctic" through the PlastFul project (PA072018) and by the Research Council of Norway through the PlastPoll project (#275172) and the FulPlast2 project (#327623). We also want to thank the anonymous reviewers for their comments.

References

Amélineau, F., Bonnet, D., Heitz, O., Mortreux, V., Harding, A.M.A., Karnovsky, N., Walkusz, W., Fort, J., Grémillet, D., 2016. Microplastic pollution in the Greenland Sea: background levels and selective contamination of planktivorous diving seabirds. Environ. Pollut. 219, 1131–1139. https://doi.org/10.1016/J.ENVPOL.2016.09.017.

Arctic Monitoring and Assessment Programme (AMAP), 2021. Litter and microplastics - monitoring plan. In: Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

Ask, A., Cusa, M., Danielsen, J., Wing Gabrielsen, G., Strand, J., 2020. Plastic Characterization in Northern Fulmars (*Fulmarus glacialis*). Nordic Council of Ministers, TemaNord. https://doi.org/10.6027/temanord2020-537.

Auman, H., Ludwig, J., Giesy, J.P., Colborn, T., 1998. Plastic ingestion by Laysan albatross chicks on Sand Island, Midway Atoll, in 1994 and 1995. In: Albatross Biology and Conservation. Chipping Norton, Australia, pp. 239–244.

Baak, J.E., Linnebjerg, J.F., Barry, T., Gavrilo, M.V., Mallory, M.L., Price, C., Provencher, J.F., 2020. Plastic ingestion by seabirds in the circumpolar Arctic: a review. Environ. Rev. 28, 506–516. https://doi.org/10.1139/er-2020-0029.

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G.W., Provencher, J.F., Rochman, C.M., van Sebille, E., Tekman, M.B., 2022. Plastic pollution in the Arctic. Nat Rev Earth Environ 3, 323–337. https://doi.org/10.1038/s43017-022-00279-8.

Bishop, C.M., Butler, P.J., Egginton, S., el Haj, A.J., Gabrielsen, G.W., 1995. Development of metabolic enzyme activity in locomotor and cardiac muscles of the migratory barnacle goose. Am. J. Phys. Regul. Integr. Comp. Phys. 269, R64–R72. https://doi.org/10.1152/ajpregu.1995.269.1.R64.

Bond, A.L., Hutton, I., Lavers, J.L., 2021. Plastics in regurgitated flesh-footed shearwater (*Ardenna carneipes*) boluses as a monitoring tool. Mar. Pollut. Bull. 168, 112428 https://doi.org/10.1016/j.marpolbul.2021.112428.

Browne, M.A., Underwood, A.J., Chapman, M.G., Williams, R., Thompson, R.C., van Franeker, J.A., 2015. Linking effects of anthropogenic debris to ecological impacts. Proc. R. Soc. B Biol. Sci. 282, 20142929. https://doi.org/10.1098/rspb.2014.2929.

Carlsson, P., Singdahl-Larsen, C., Lusher, A.L., 2021. Understanding the occurrence and fate of microplastics in coastal Arctic ecosystems: the case of surface waters, sediments and walrus (*Odobenus rosmarus*). Sci. Total Environ. 792, 148308 https://doi.org/10.1016/j.scitotenv.2021.148308.

Charlton-Howard, H.S., Bond, A.L., Rivers-Auty, J., Lavers, J.L., 2023. 'Plasticosis': Characterising macro- and microplastic-associated fibrosis in seabird tissues. J. Hazard. Mater. 450, 131090 https://doi.org/10.1016/j.jhazmat.2023.131090.

Collard, F., Ask, A., 2021. Plastic ingestion by Arctic fauna: a review. Sci. Total Environ. 786, 147462 https://doi.org/10.1016/j.scitotenv.2021.147462.

Collard, F., Bangjord, G., Herzke, D., Gabrielsen, G.W., 2022a. Plastic burdens in northern fulmars from Svalbard: looking back 25 years. Mar. Pollut. Bull. 185, 114333 https://doi.org/10.1016/j.marpolbul.2022.114333.

Collard, F., Leconte, S., Danielsen, J., Halsband, C., Herzke, D., Harju, M., Tulatz, F., Gabrielsen, G.W., Tarroux, A., 2022b. Plastic ingestion and associated additives in Faroe Islands chicks of the northern fulmar *Fulmarus glacialis*. Water Biology and Security 1, 100079. https://doi.org/10.1016/j.watbs.2022.100079.

De Rovere, F., Langone, L., Schroeder, K., Miserocchi, S., Giglio, F., Aliani, S., Chiggiato, J., 2022. Water Masses Variability in Inner Kongsfjorden (Svalbard) During 2010–2020. Front. Mar. Sci. 9 https://doi.org/10.3389/fmars.2022.741075.

Fackelmann, G., Sommer, S., 2019. Microplastics and the gut microbiome: how chronically exposed species may suffer from gut dysbiosis. Mar. Pollut. Bull. 143, 193–203. https://doi.org/10.1016/j.marpolbul.2019.04.030.

Fackelmann, G., Pham, C.K., Rodríguez, Y., Mallory, M.L., Provencher, J.F., Baak, J.E., Sommer, S., 2023. Current levels of microplastic pollution impact wild seabird gut microbiomes. Nat Ecol Evol. https://doi.org/10.1038/s41559-023-02013-z.

van Franeker, J.A., 1985. Plastic ingestion in the North Atlantic fulmar. Mar. Pollut. Bull. 16, 367–369.

van Franeker, J.A., 2004. Save the North Sea Fulmar-Litter-EcoQO Manual Part 1: Collection and Dissection Procedures. Wageningen.

van Franeker, J.A., 2012. Plastic ingestion by fulmars at the Faroe Islands. In: The Fulmar on the Faroe Islands. Torshavn, pp. 82–85.

van Franeker, J.A., Heubeck, M., Fairclough, K., Turner, D.M., Grantham, M., Stienen, E., Guse, N., Pedersen, J., Olsen, K.-O., Andersson, P.J., Olsen, B., 2005. 'Save the North Sea' Fulmar Study 2002–2004: A Regional Pilot Project for the Fulmar-Litter-EcoQO in the OSPAR Area. Wageningen.

van Franeker, J.A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., Hansen, P.-L., Heubeck, M., Jensen, J.-K., Le Guillou, G., Olsen, B., Olsen, K.-O., Pedersen, J., Stienen, E.W.M., Turner, D.M., 2011. Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea. Environ. Pollut. 159, 2609–2615. https://doi.org/10.1016/j.envpol.2011.06.008.

van Franeker, J.A., Jensen, J.-K., Simonsen, P.J., Bravo Rebolledo, E.L., Kühn, S., 2022. Plastics in stomachs of northern fulmars *Fulmarus glacialis* collected at sea off east Greenland: latitude, age, sex and season. Mar. Biol. 169, 45. https://doi.org/10.1007/s00227-022-04029-8.

Furness, R.W., 1985. Plastic particle pollution: accumulation by procellariiform seabirds at Scottish Colonies. Mar. Pollut. Bull. 16, 103–106. https://doi.org/10.1016/0025-326X(85)90531-4.

Halsband, C., Herzke, D., 2019. Plastic litter in the European Arctic: what do we know? Emerg Contam 5, 308–318. https://doi.org/10.1016/j.emcon.2019.11.001.

Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N. P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53, 1039–1047. https://doi.org/10.1021/acs.est.8b05297.

Hegseth, E.N., Sundfjord, A., 2008. Intrusion and blooming of Atlantic phytoplankton species in the high Arctic. J. Mar. Syst. 74, 108–119. https://doi.org/10.1016/j.jmarsys.2007.11.011.

Hop, H., Pearson, T., Hegseth, E.N., Kovacs, K.M., Wiencke, C., Kwasniewski, S., Eiane, K., Mehlum, F., Gulliksen, B., Wlodarska-Kowalczuk, M., Lydersen, C., Weslawski, J.M., Cochrane, S., Gabrielsen, G.W., Leakey, R.J.G., Lønne, O.J., Zajaczkowski, M., Falk-Petersen, S., Kendall, M., Wängberg, S.-Å., Bischof, K., Voronkov, A.Y., Kovaltchouk, N.A., Wiktor, J., Poltermann, M., Prisco, G.D., Papucci, C., Gerland, S., 2002. The marine ecosystem of Kongsfjorden, Svalbard. Polar Res. 21, 167–208. https://doi.org/10.3402/polar.v21i1.6480.

Jiang, Y., Yang, F., Zhao, Y., Wang, J., 2020. Greenland Sea Gyre increases microplastic pollution in the surface waters of the Nordic Seas. Sci. Total Environ. 712, 136484 https://doi.org/10.1016/j.scitotenv.2019.136484.

Kenyon, K.W., Kridler, E., 1969. Laysan Albatross swallow indigestible matter. Auk 86, 339–343. https://doi.org/10.2307/4083505.

Kühn, S., van Oyen, A., Bravo Rebolledo, E.L., Ask, A.V., van Franeker, J.A., 2021. Polymer types ingested by northern fulmars (*Fulmarus glacialis*) and southern hemisphere relatives. Environ. Sci. Pollut. Res. 28, 1643–1655. https://doi.org/10.1007/s11356-020-10540-6.

Lavers, J.L., Bond, A.L., 2023. Pumice ingestion in seabirds: interannual variation, and relationships with chick growth and plastic ingestion. Mar. Biol. 170, 55. https://doi.org/10.1007/s00227-023-04203-6.

Liboiron, M., Zahara, A., Hawkins, K., Crespo, C., de Moura Neves, B., Wareham-Hayes, V., Edinger, E., Muise, C., Walzak, M.J., Sarazen, R., Chidley, J., Mills, C., Watwood, L., Arif, H., Earles, E., Pijogge, L., Shirley, J., Jacobs, J., McCarney, P., Charron, L., 2021. Abundance and types of plastic pollution in surface waters in the Eastern Arctic (Inuit Nunangat) and the case for reconciliation science. Sci. Total Environ. 782, 146809 https://doi.org/10.1016/j.scitotenv.2021.146809.

Lusher, A.L., Tirelli, V., O'Connor, I., Officer, R., 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Rep. 5, 14947. https://doi.org/10.1038/srep14947.

Mallory, M.L., 2008. Marine plastic debris in northern fulmars from the Canadian high Arctic. Mar. Pollut. Bull. 56, 1501–1504. https://doi.org/10.1016/j.marpolbul.2008.04.017.

Mallory, M.L., Hatch, S.A., Nettleship, D.N., 2020. Northern fulmar (*Fulmarus glacialis*), version 1.0. In: Billerman, S.M. (Ed.), Birds of the World. NY.

Nania, T.G., Shugart, G.W., 2021. Are plastic particles reduced in size in seabirds' stomachs? Mar. Pollut. Bull. 172, 112843. https://doi.org/10.1016/j.marpolbul.2021.112843.

OSPAR, 2010. The OSPAR System of Ecological Quality Objectives for the North Sea: A Contribution to OSPAR's Quality Status Report 2010. OSPAR Publication 404/2009. OSPAR Commission London, and Rijkswaterstaat VenW, Rijswijk, 16pp. http://qsr2010.ospar.org/media/assessments/EcoQO/EcoQO_P01-16_complete.pdf.

OSPAR Commission, 2008. Background document for the EcoQO on plastic particles in stomachs of seabirds. In: OSPAR Commission, Biodiversity Series Publication Number: 355/2008. OSPAR London, 18pp. https://www.ospar.org/ospar-data/p00355_ecoqo%20plastics%20in%20seabird%20stomachs.pdf, (accessed 07th August 2023).

OSPAR Commission, 2015. Coordinated Environmental Monitoring Programme (CEMP) Guidelines for Monitoring and Assessment of Plastic Particles in Stomachs of Fulmars in the North Sea area. OSPAR Commission Agreement 2015-03 (Source: EIHA 15/5/12 Add.1), 26pp. http://www.ospar.org/convention/agreements?q=fulmar&t=32281&a=&s.

Polyakov, I.V., Beszczynska, A., Carmack, E.C., Dmitrenko, I.A., Fahrbach, E., Frolov, I.E., Gerdes, R., Hansen, E., Holfort, J., Ivanov, V.V., Johnson, M.A., Karcher, M., Kauker, F., Morison, J., Orvik, K.A., Schauer, U., Simmons, H.L., Skagseth, Ø., Sokolov, V.T., Steele, M., Timokhov, L.A., Walsh, D., Walsh, J.E., 2005. One more step toward a warmer Arctic. Geophys. Res. Lett. 32 https://doi.org/10.1029/2005GL023740.

Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borrelle, S.B., Bravo Rebolledo, E.L., Hammer, S., Kühn, S., Lavers, J.L., Mallory, M.L., Trevail, A., van Franeker, J.A., 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. Anal. Methods 9, 1454–1469. https://doi.org/10.1039/C6AY02419J.

Rivers-Auty, J., Bond, A.L., Grant, M.L., Lavers, J.L., 2023. The one-two punch of plastic exposure: macro- and micro-plastics induce multi-organ damage in seabirds. J. Hazard. Mater. 442, 130117 https://doi.org/10.1016/j.jhazmat.2022.130117.

Robards, M.D., Piatt, J.F., Wohl, K.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the subarctic North Pacific. Mar. Pollut. Bull. 30, 151–157. https://doi.org/10.1016/0025-326X(94)00121-O.

Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.-C., Werorilangi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci. Rep. 5, 14340. https://doi.org/10.1038/srep14340.

Santos, R.G., Andrades, R., Fardim, L.M., Martins, A.S., 2016. Marine debris ingestion and Thayer's law – the importance of plastic color. Environ. Pollut. 214, 585–588. https://doi.org/10.1016/j.envpol.2016.04.024.

Skórka, P., Wójcik, J.D., 2008. Habitat utilisation, feeding tactics and age related feeding efficiency in the Caspian Gull *Larus cachinnans*. J. Ornithol. 149, 31–39. https://doi.org/10.1007/s10336-007-0208-3.

Snæþórsson, A.Ö., 2021. Plast í meltingarvegi fýla við Ísland árið 2020. Husavik, Iceland.

Sühring, R., Baak, J.E., Letcher, R.J., Braune, B.M., de Silva, A., Dey, C., Fernie, K., Lu, Z., Mallory, M.L., Avery-Gomm, S., Provencher, J.F., 2022. Co-contaminants of microplastics in two seabird species from the Canadian Arctic. Environmental Science and Ecotechnology 12, 100189. https://doi.org/10.1016/j.ese.2022.100189.

Tanaka, K., van Franeker, J.A., Deguchi, T., Takada, H., 2019. Piece-by-piece analysis of additives and manufacturing byproducts in plastics ingested by seabirds: implication for risk of exposure to seabirds. Mar. Pollut. Bull. 145, 36–41. https://doi.org/10.1016/j.marpolbul.2019.05.028.

Thayer, A.H., 1896. The law which underlies protective coloration. Auk 124–129.

Trevail, A.M., Gabrielsen, G.W., Kühn, S., Van Franeker, J.A., 2015. Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (*Fulmarus glacialis*). Polar Biol. 38, 975–981. https://doi.org/10.1007/s00300-015-1657-4.

Tulatz, F., Gabrielsen, G.W., Bourgeon, S., Herzke, D., Krapp, R., Langset, M., Neumann, S., Lippold, A., Collard, F., 2023. Implications of Regurgitative feeding on plastic loads in northern fulmars (*Fulmarus glacialis*): a study from Svalbard. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.2c05617.

Verlis, K.M., Campbell, M.L., Wilson, S.P., 2013. Ingestion of marine debris plastic by the wedge-tailed shearwater *Ardenna pacifica* in the Great Barrier Reef, Australia. Mar. Pollut. Bull. 72, 244–249. https://doi.org/10.1016/j.marpolbul.2013.03.017.

Vlietstra, L.S., Parga, J.A., 2002. Long-term changes in the type, but not amount, of ingested plastic particles in short-tailed shearwaters in the southeastern Bering Sea. Mar. Pollut. Bull. 44, 945–955. https://doi.org/10.1016/S0025-326X(02)00130-3.

Werner, S., Budziak, A., van Franeker, J., Galgani, F., Hanke, G., Maes, T., Matiddi, M., Nilsson, P., Oosterbaan, L., Priestland, E., Thompson, R., Veiga, J., Vlachogianni, T., 2016. Harm caused by marine litter. In: MSFD GES TG Marine Litter - Thematic Report, Technical report. ed. JRC.

Wilcox, C., Van Sebille, E., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. 112, 11899–11904. https://doi.org/10.1073/pnas.1502108112.

Youngren, S.M., Rapp, D.C., Hyrenbach, K.D., 2018. Plastic ingestion by Tristram's storm-petrel (*Oceanodroma tristrami*) chicks from French frigate shoals, Northwestern Hawaiian Islands. Mar. Pollut. Bull. 128, 369–378. https://doi.org/10.1016/j.marpolbul.2018.01.053.