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Characterising the plastics ingested by northern fulmars (*Fulmarus glacialis*) across the north-east Atlantic Ocean

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Master's thesis in biological chemistry

supervised by
Geir Wing Gabrielsen, Norwegian Polar Institute
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Abstract

Marine plastic pollution affects a myriad of species across the world. The interactions between wildlife and marine plastics can be broadly categorised as either entanglement or ingestion of plastics. Seabirds, and especially Procellariiformes, have been identified as particularly vulnerable to ingesting plastics. The ingestion of plastics by the northern fulmar (*Fulmarus glacialis*) has been studied for many years across its distribution range as part of monitoring efforts investigating the status of plastic pollution in the ocean. However, there is a lack of knowledge regarding the polymer composition of the ingested plastic, which is important for the development of meaningful mitigation strategies. The aim of this study was therefore to assess the degree of plastic ingestion and particularly the polymer composition of ingested plastics by northern fulmars from the Faroe Islands, Iceland, Svalbard and north-east Greenland, using FTIR spectroscopy. The results show that the majority of fulmars from all four regions ingested plastics, with individuals from the Faroe Islands exhibiting significantly higher levels compared to those from Svalbard and north-east Greenland. Similarly, the Icelandic fulmars had ingested significantly more plastics than the Greenlandic birds. For all four regions, the majority of ingested plastics was composed of polyethylene, followed by polypropylene and polystyrene. The results indicate differences in the polymer profile between the four regions which should be the subject of future research efforts.

Sammendrag

Karakterisering av plast spist av havhest

Marin plastforurensning påvirker utallige arter over hele verden. Interaksjonene mellom plast og dyreliv kan klassifiseres som innvikling i plast eller at dyr spiser plast. Sjøfugler, og spesielt medlemmer av Procellariiformes-ordenen (Stormfugler), er spesielt utsatte for å spise plast. Plastinntaket til havhest (*Fulmarus glacialis*) fra Nordsjøen, det nordlige Atlanterhavet og det nordlige Stillehavet har blitt undersøkt i en årrekke som en måte å kartlegge og studere mengden og typen plast i havet. Til tross for dette så er det et kunnskapshull når det kommer til den kjemiske komposisjonen av plasten havhesten spiser. Dette er viktig informasjon å ha som innspill til utvikling av strategier for å bekjempe marin plastforurensning—som bare vil bli viktigere i tiden som kommer. Formålet med dette studiet var derfor å undersøke mageinnholdet av plast i havhest fra Færøyene, Island, Svalbard og nordøst Grønland for å identifisere polymer-komposisjonen til plasten ved bruk av FTIR spektroskopi. Resultatene viser at flertallet av havhestene fra alle de fire regionene hadde spist plast, samtidig som at fuglene fra Færøyene hadde spist betydelig mer plast enn fuglene fra Svalbard og nordøst Grønland. De islandske havhestene hadde også spist betydelig mer plast enn de grønlandske fuglene. I alle de fire regionene var hovedparten av plasten polyetylen, fulgt av polypropylen og polystyren. Det er imidlertid indikasjoner på at polymerprofilen var forskjellig mellom regionene og nærmere undersøkelser av dette anbefales.

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Abbreviations

ABS Acrylonitrile Butadiene Styrene.

ATR Attenuated Total Reflectance.

DMS Dimethyl Sulfide.

EcoQO Ecological Quality Objective.

FO Frequency of Occurrence.

FTIR Fourier Transform Infrared.

GI Gastrointestinal.

HDPE High Density Polyethylene.

HQI Hit Quality Index.

IUCN International Union for Conservation of Nature.

LDPE Low Density Polyethylene.

LLDPE Linear Low Density Polyethylene.

PA Polyamide.

PE Polyethylene.

PET Polyethylene Terephthalate.

PP Polypropylene.

PS Polystyrene.

PU Polyurethane.

PVC Polyvinyl Chloride.

Chapter 1

Introduction

1.1 Marine plastic pollution

Every year as much as 12.7 million metric tons of plastics enter the world's oceans, according to an estimate based on data from 2010 (Jambeck et al., 2015). Once the plastics is in the marine environment it is easily transported and plastic contamination has been detected in deep ocean sediments (Cauwenberghe et al., 2013), on the beaches of uninhabited islands (Lavers et al., 2019a; Lavers et al., 2017) and in the oceans of the remote polar regions (Cincinelli et al., 2017; Isobe et al., 2017; Kanhai et al., 2018; Kanhai et al., 2019).

Marine plastic pollution is estimated to cost 1.27 billion USD annually to the Asian-Pacific economies alone (McIlgorm et al., 2011), it diminishes the aesthetical quality of open oceans and coastlines worldwide, and there are numerous documented detrimental effects on wildlife (Rochman et al., 2013; Roman et al., 2019a; Waluda et al., 2013; Wilcox et al., 2014). At the same time, global plastic production continues to increase, with a production of almost 350 million tons of plastics in 2017 (PlasticsEurope, 2018). Thus, issues related to marine plastic pollution will likely continue to escalate, prompting the United Nations to declare "war" on marine plastics (United Nations Environment Programme, 2017).

1.1.1 Sources of marine plastics

The sources of marine plastics are diverse, but the common denominator for all is human error—accidental or deliberate. The main sources are land-based, where discarded plastics are swept into nearby waterways by wind or rain and are ultimately carried out to sea (Derraik, 2002; Sheavly et al., 2007). Local littering, for example by beach-goers, also accounts for a considerable portion of marine plastics, especially on a local scale (Willis et al., 2017). Even though plastics are recyclable, the rate at which plastic products are properly disposed of and recycled is at only 14% (Neufeld et al., 2016). The lack of recycling also has a negative economical impact, with an estimated $80 - 120$ billion USD lost every year through plastics discarded after only one use (Neufeld et al., 2016). Discarded plastics entering municipal solid waste disposal systems without subsequent recycling can enter the marine environment through inadequately designed landfills, open dumps and even intentional dumping into waterways (Boadi et al., 2003; Shekdar, 2009; Turan et al., 2009). The plastics industry itself is the source of a commonly found type of plastics: industrial pellets (also called “nurdles”) which are the virgin stock of plastics (Costa et al., 2009; Lavers et al., 2019b; McDermid et al., 2004; Trevail et al., 2015a).

Although not as large as those from land, ocean-based sources of plastics can be highly significant locally, as evidenced on beaches and coastlines close to areas of extensive fisheries where the majority of marine plastics washed ashore is related to the fishing industry (Bergmann et al., 2017; Galgani et al., 2015; Gregory et al., 2003; Walker et al., 1997). In 1988 MARPOL Annex V was implemented, banning the disposal of plastics from ships, including fishing gear and equipment. However, while there is not much information available, research indicates that the ban has had no effect on the prevalence of marine plastics (Henderson, 2001). Difficulties in enforcing the ban, combined with high costs of waste disposal at port, likely lead to many ships illegally dumping plastic waste at sea (Rakestraw, 2012).

1.1.2 Fate of marine plastics

Once the plastic has entered the marine environment, it is subject to mechanical and photochemical weathering processes. Wave and wind action exert physical pressure and stress on the plastic while it is being made increasingly brittle and fragile by exposure to ultraviolet light (Halle et al., 2016; Jahnke et al., 2017). Consequently, large pieces of plastics are broken down into increasingly smaller fragments, forming micro- and nano-plastics (Costa et al., 2016). The time frame for this is largely unknown and likely varies considerably across the world’s oceans, depending on the different light and temperature conditions. Furthermore, the polymer composition of the plastics[1] also affects the rate of fragmentation (Song et al., 2017).

The densities of the different polymers vary and determine whether plastics of a given chemical composition will float or sink in seawater (Richard et al., 2011). Marine plastics provide a platform for bacterial and algal growth, termed biofouling (Lobelle et al., 2011; Zettler et al., 2013). This biofouling may alter the buoyancy of plastics, causing plastics which ordinarily float to sink (Fazey et al., 2016). The sinking and subsequent incorporation of plastics into the sediment is believed to act as a sink for marine plastics, especially in deep-ocean sediments (Woodall et al., 2014). Prior to potentially sinking, however, floating marine plastics can be transported great distances (Ebbesmeyer et al., 1994), accumulate in oceanic gyres (Eriksen et al., 2013; Law et al., 2010) and wash ashore (Bergmann et al., 2017; Lavers et al., 2017), amongst other things. These floating and beach-washed plastics are of major concern due to their impact on wildlife worldwide.

[1] Plastic is a general term used to describe synthetically produced polymers that are often, but not exclusively, derived from petroleum products. There is a multitude of different polymers, each with different physicochemical properties making them suitable for a range of applications (PlasticsEurope, 2018).

1.1.3 Effects of marine plastics on wildlife

Marine plastic pollution affects wildlife from zooplankton to whales from pole to pole (Baulch et al., 2014; Bergmann et al., 2017; Desforges et al., 2015; Hofmeyr et al., 2006). Over 660 species, 15% of which are on the International Union for Conservation of Nature (IUCN) Red List for threatened and endangered species, have been documented to interact with marine plastics (UNEP, 2016). Broadly speaking, these interactions between wildlife and plastics can be classified as either entanglement or ingestion.

Entanglement

Wildlife can become entangled in nets, lines and rope, six-pack rings for beverage cans and other plastic debris (Colmenero et al., 2017; Good et al., 2009; Laist, 1997; Richardson et al., 2019; Waluda et al., 2013). These entanglements can lead to lacerations and other injuries which may also become infected, reduced mobility which could affect the ability to feed and avoid predation, exhaustion due to the increased weight and drag, and drowning if the animal is unable to surface for air (Good et al., 2009; Laist, 1997). Entanglements have been documented in numerous species, including fish, sharks, turtles, seals and sealions, dolphins and whales, birds, dugongs and manatees (Cliff et al., 2002; Good et al., 2009; Laist, 1997; Reinert et al., 2017). It has even been observed for terrestrial species such as the Svalbard reindeer (*Rangifer tarandus platyrhynchus*) which frequently forage along the shoreline (Hansen et al., 2019) and hence risk entangling their antlers in beach-washed plastics (Bergmann et al., 2017).

Seabirds have also been shown to use plastics as nest material (Hartwig et al., 2007; Verlis et al., 2014). This appears to be particularly common for members of the Sulidae family which comprises gannets and boobies. Votier et al. (2011) examined plastics incorporation in nests of northern gannets (*Morus bassanus*) breeding in Wales, and reported that the average nest contained almost 500 g of plastics. Each year an average of just over 60 gannets were entangled in plastic nest material, with the majority of the entangled individuals being chicks.

Ingestion

Another, and less immediately obvious, problem is the ingestion of marine plastics by wildlife. Seabirds have been identified as being particularly vulnerable to plastic ingestion (Moser et al., 1992; Wilcox et al., 2015), but it has been shown to occur in a variety of species, from zooplankton to whales (Baulch et al., 2014; Desforges et al., 2015).

A range of seabirds ingest plastics, yet members of the Procellariiformes order (e.g., the albatrosses, petrels, shearwaters and fulmars) are especially susceptible to ingesting plastics (Roman et al., 2019a) and are also among the most threatened group of birds (Paleczny et al., 2015). As pelagic seabirds, they feed exclusively at sea by picking up prey items from the sea surface (Prince et al., 1987). Furthermore, the connection between the proventriculus and the gizzard is narrow, hindering regurgitation and thus leading to accumulation of plastics in the stomach (Azzarello et al., 1987). Despite this, parental transfer of plastics to nestlings does occur (Acampora et al., 2017; Lavers et al., 2014; Rodríguez et al., 2012). In flesh-footed shearwaters (*Puffinus carneipes*), chicks with higher levels of plastics had poorer body condition compared to chicks with low or no stomach plastic contents (Lavers et al., 2014).

Other effects of ingested plastics include ulceration of the stomach and dietary dilution, where the intake of plastics reduce the intake of actual food (Azzarello et al., 1987; Pierce et al., 2004; Roman et al., 2019b). Mortalities from blockages of the gastrointestinal (GI) tract, obstructions causing infections, and perforations of the GI tract have been documented for seabirds (Pierce et al., 2004; Roman et al., 2019a).

The proclivity of the Procellariiformes to ingest plastics makes them ideal species to monitor marine plastic pollution. A long-running monitoring effort uses the stomach plastic content of the northern fulmar (*Fulmarus glacialis*) to monitor the abundance and composition of marine debris in the North Sea and north Atlantic Ocean (Franeker et al., 2011; Franeker et al., 2002).

1.2 Northern fulmars

The northern fulmar (hereafter referred to as fulmar, shown in Figure 1.1) is a pelagic seabird with a wide distribution in the northern hemisphere; it is found around the northern Atlantic, Arctic and northern Pacific Oceans (Anker-Nilssen et al., 2000; Hatch, 1993). Fulmars are a long-lived species and reach sexual maturation late. They begin reproducing when they are around $8 - 12$ years of age and are usually monogamous and bond for life. The female lays one egg and both parents share the incubation and chick-rearing duties (Figure 1.1b shows fulmars incubating). The incubation takes roughly 50 days and the chick fledges *circa* 50 days after hatching (Mallory, 2006, and references therein). Fulmars feed exclusively at sea, picking up prey such as squid, fish and polychaetes from the sea surface (Anker-Nilssen et al., 2000). They are competent fliers and can cover large distances in search of food (Weimerskirch et al., 2001). During the winter months they migrate away from the breeding sites and lead a fully pelagic lifestyle (Lyngs, 2003; Mallory et al., 2008).

Previous studies have shown consistently high levels of ingested plastics by fulmars (Avery-Gomm et al., 2018; Donnelly-Greenan et al., 2014; Kühn et al., 2012; Trevail et al., 2015a). While the levels are highest close to mainland Europe and large population centres, Trevail et al. (2015a) also found elevated levels in fulmars from Svalbard.

Many studies reporting on ingested plastics by fulmars divide the plastics into different categories, as is recommended by Provencher et al. (2017). This facilitates comparisons across regions as well as informing the development of mitigation policies and strategies for marine plastic pollution. However, there is a knowledge gap when it comes to the polymer composition of the ingested plastics by fulmars. This issue was also highlighted by Provencher et al. (2017), who recommended that future studies should investigate the polymer composition of the plastics ingested by fauna.

Thus far only one article has been published where plastics ingested by fulmars have

(a) Swimming (b) Breeding

Figure 1.1: Northern fulmars (*Fulmarus glacialis*) in Svalbard. (a) Photo courtesy of Geir W. Gabrielsen, Norwegian Polar Institute; (b) Photo by Amalie V. Ask.

been identified (Tanaka et al., 2019). In general, there is not much information available on the chemical composition of ingested plastics by wildlife, except for one study on little auks (*Alle Alle*) (Avery-Gomm et al., 2016), one on sea turtles (Jung et al., 2018b) and two on fish (Collard et al., 2015; Lefebvre et al., 2019).

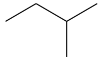
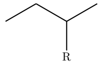
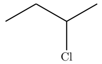
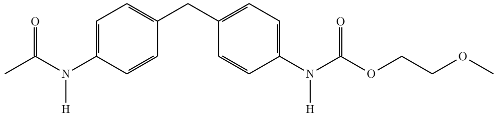
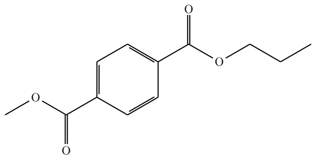
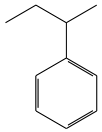
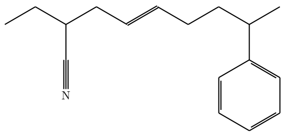
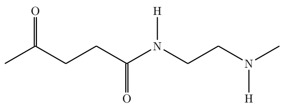
Table 1.1 shows the chemical structure and common uses for the main types of polymers produced in Europe (PlasticsEurope, 2018). Polyethylene and polypropylene are the two most produced plastic polymers and a major application for both is in the manufacture of single-use plastics, for example as packaging for food and other items, bags and bottles. Moreover, both polyethylene and polypropylene float in seawater (Richard et al., 2011), and it is therefore expected that the majority of plastics ingested by fulmars are polyethylene and polypropylene, reflecting the production and application of these polymers. This was indeed the case for the Faroese fulmars investigated by Tanaka et al. (2019).

Given the severity and extent of marine plastic pollution and the urgent need for viable and effective solutions to mitigate it, research on the type and composition of plastics in the marine environment – and the regional differences therein – is of the utmost importance.

1.3 Aim of study and hypotheses

The aims of this study are to (1) quantify and (2) characterise the plastics ingested by fulmars from the Faroe Islands, Iceland, Svalbard and north-east Greenland, to better understand the geographical differences in plastic ingestion rates as well as the composition of ingested plastics. This will be achieved through visual inspection and Fourier-transform infrared (FTIR) spectroscopy to determine the quantity, type and polymer composition of the ingested plastics. It is hypothesized that fulmars from the Faroe Islands and Iceland ingest higher levels of plastics, with a greater variation in the polymer composition of the plastics, than fulmars inhabiting the more remote regions of Svalbard and north-east Greenland.

Table 1.1: The chemical structure of the monomer building blocks and common uses for the main polymers produced in Europe in 2017 (PlasticsEurope, 2018).

Name	Monomer	Common uses
Polypropylene		Food packaging, bags, automobile parts
Polyethylene		Food packaging, bottles, toys, containers
Polyvinyl chloride		Building materials, hoses, cable insulation
Polyurethane		Building insulation, pillows and mattresses
Polyethylene terephthalate		Bottles
Polystyrene		Packaging, cups
Acrylonitrile butadiene styrene		Medical devices, LEGO, keyboard caps
Polyamide		Nylons

Chapter 2

Materials and methods

2.1 Locations

The fulmars whose stomach plastic contents were used in this study were sampled at four different locations (shown in Figure 2.1).

2.1.1 Faroe Islands

A total of 55 fulmar fledglings from the Faroe Islands were captured at sea by local hunters in northern Faroe Islands on 5 September 2017 as part of a traditional hunt. The stomachs of the 55 fulmars were saved by the hunters after removal and frozen in individual plastic bags at $-20°C$. No biometric data was gathered for these fulmars.

The way the stomachs were handled when they were removed from the fulmars resulted in them being "squeezed" and some were torn, meaning that plastics was potentially lost. No data has previously been reported for these fulmars.

2.1.2 Iceland

A total of 40 fulmars were shot at sea near Bolungarvìk, north-west Iceland. Of the 40 fulmars, 37 were shot on 15 October 2013 and three on 17 February 2014. Four of the fulmars were female and 36 were male. They ranged from juveniles to adults. The stomachs were stored in individual plastic bags at $-20°C$.

A subset of the data on mass and number of ingested plastic particles has previously been reported by Trevail et al. (2015b), but the full dataset is presented here for the first time.

2.1.3 Svalbard

A total of 40 fulmars were shot in Isfjorden, Svalbard between 21–23 September 2013. Of the 40 fulmars, 21 were female and 19 were male. They ranged from juveniles to adults.

Figure 2.1: The sampling locations of northern fulmars (*Fulmarus glacialis*) from the Faroe Islands (diamond), Iceland (circle), Svalbard (triangle) and north-east Greenland (squares).

The dissections were performed at the University Centre of Svalbard, Longyearbyen, according to the protocol outlined in Franeker (2004).

The data on mass and number of ingested plastic particles have already been reported by Trevail et al. (2015a). Furthermore, the plastic ingested by 38 out of the 40 fulmars have previously been analysed with FTIR spectroscopy (S. Kühn, unpublished). The ingested plastics by the two remaining fulmars were analysed with FTIR spectroscopy in the current study and reported here.

2.1.4 Greenland

A total of 31 fulmars were shot at sea in north-east Greenland between 25 August and 9 September 2017. The stomachs were stored in individual plastic bags at $-20°C$. No data has previously been reported for these fulmars.

The fulmars were shot during a research cruise sailing on a transect from Svalbard to Greenland, and while some of the sampling stations are close to Svalbard, most of the fulmars were shot at stations closer to Greenland. Therefore it was decided to treat them separately from the Svalbard fulmars during the analyses.

Figure 2.2: Stomach plastics content of a northern fulmar (*Fulmarus glacialis*) from north-east Greenland captured in 2017.

2.2 Stomach dissection

The fulmar stomachs, comprising the esophagus, proventriculus and gizzard, were dissected to obtain any ingested plastics.

The Faroese fulmar stomachs were dissected at Wageningen Marine Research Center, Den Helder, the Netherlands, during October 2018. The stomachs of the Greenlandic fulmars were dissected at Aarhus University, Risø, Denmark, during April 2019.

The dissections of the stomachs were done by first severing the connection between the proventriculus and gizzard using scissors. The contents of the proventriculus and gizzard were examined separately, by carefully cutting them open with the scissors. The contents were then emptied into a 1 mm mesh sieve. Under gently running water, the contents were thoroughly searched and any items of interest were removed and placed in a petri dish. The emptied stomachs were again frozen at −20°C for potential use in future studies.

Stomach contents were examined under a stereo microscope to identify plastic pieces. This was achieved mainly through visual inspection, but also by touch and sound. Pieces identified as plastic were further categorised into industrial plastics (i.e., pellets) and user plastics (sheets, threads, foam, fragments and other). They were then left to air dry completely at room temperature. Figure 2.2 shows the stomach plastics content of one fulmar from north-east Greenland prior to categorisation.

2.3 Weighing and measuring the plastic

Grouped by category, the dry pieces were weighed for each bird (AT261 DeltaRange, Mettler Toledo, OH, USA), combining the contents from the proventriculus and gizzard. However, for the Greenlandic fulmars, the plastic pieces were all weighed individually as explained in Section 2.5.3.

Afterwards, the pieces were placed on mm-paper, photographed, and their size noted. The pieces were sized as either micro (< 5 mm) or meso (≥ 5 mm). Each individual piece was given a unique code and stored separately in an Eppendorf tube.

2.4 FTIR spectroscopy analysis

The Fourier-transform infrared (FTIR) spectroscopy analysis was performed at Aarhus University, Risø, Denmark, between February–April 2019.

2.4.1 Theoretical background

Infrared spectroscopy, a type of vibrational spectroscopy, utilizes electromagnetic radiation in the infrared range to gain information on the type of chemical bonds present in a sample (Siesler et al., 2002). Chemical bonds vibrate at different energies, so by passing radiation at a range of frequencies through a sample and detecting at which frequencies absorption occurs, the presence of specific bonds is determined (Bacsik et al., 2004; Griffiths et al., 2007; Pasquini, 2018).

Furthermore, instead of passing each frequency separately through the sample, the sample can be irradiated by a beam of infrared light containing the entire range of desired frequencies simultaneously. This drastically reduces the time necessary to analyse the sample. But by using all the frequencies concurrently, a mathematical transformation of the output is required to convert the resultant signal into a spectrum. This is achieved by the Fourier transformation (Bacsik et al., 2004; Griffiths et al., 2007).

For solid samples, however, it is usually not possible to transmit the infrared radiation through the sample. To be able to use infrared spectroscopy to analyse these types of samples, a technique termed attenuated total reflectance (ATR) is used (Man et al., 2010). With this, an evanescent wave of infrared light hits the surface of the sample, penetrates a few micrometers and is reflected back. This technique requires a crystal with a higher refractive index than that of the sample and that the crystal and sample are in close contact with each other.

The Fourier transform infrared spectroscopy with the ATR technique is commonly used to analyse the chemical composition of plastic pieces (Shim et al., 2017).

2.4.2 Instrumental set-up

The spectrometer used was a 4500a portable FTIR with an ATR diamond crystal (Agilent Technologies, CA, USA).

The spectral range was set to the full 4000–650 cm^{-1} available for the instrument. 64 scans were performed for establishing the background, while 32 scans were done when analysing samples. The resolution was set to 2 cm^{-1}.

After obtaining a spectrum of the sample, it was compared to reference spectra in the Aarhus University microplastics library using a similarity search algorithm (MicroLab Software, Agilent Technologies, CA, USA). The matches were ranked according to the Hit Quality Index (HQI), assigning a number between zero and one, where one is a perfect match between sample and reference spectra.

2.4.3 Analysis

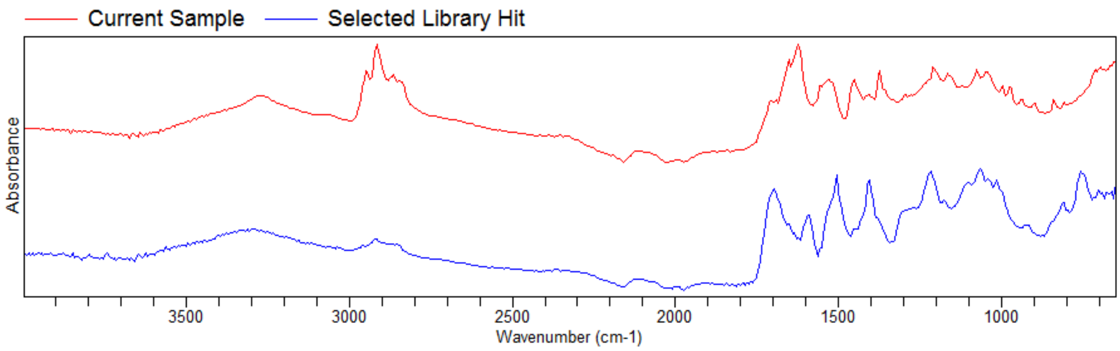
The pieces were placed on the diamond crystal and firmly clamped down to minimize the air between the crystal and the sample. Many of the pieces had a layer of proteinaceous biofilm masking the spectra of the polymer. For these pieces, the surface layer was either cut off using a scalpel, scratched off with a needle, cleaned with ethanol, or a combination of these depending on the piece. Figure 2.3 demonstrates the effect the biofilm has on the quality of the spectrum (in red). Cutting off a thin slice of the sample was preferred, but unpractical with certain types of samples such as threads, sheets and foam. Some fragments were also very fragile and brittle.

2.4.4 Quality assurance

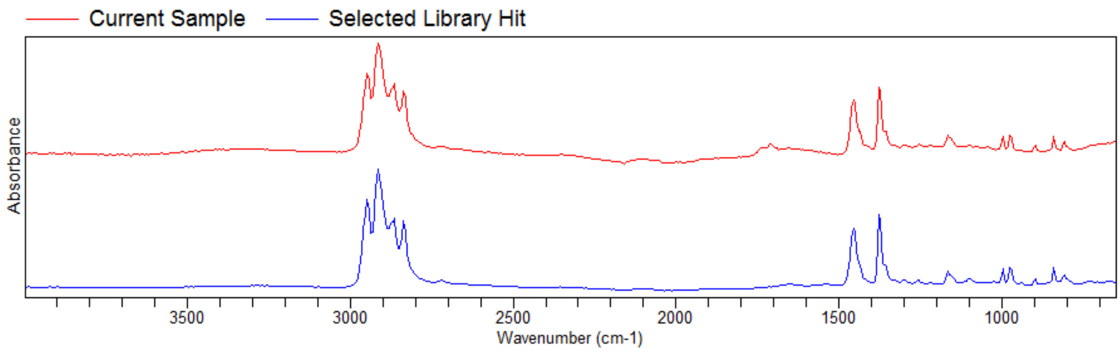
Prior to analysing samples, the crystal was cleaned with ethanol and the background established. Before placing the sample on the crystal, a check was made that the spectrometer was not detecting anything (i.e., that the background was completely removed). If the baseline was showing the presence of e.g., CO_2 or water, the crystal was cleaned again and a new background calibration performed. This was repeated if necessary until an appropriate baseline was obtained.

For each scanned sample, the resulting spectrum was visually examined and the chemical composition determined based on signature peaks. The composition of the sample was only accepted if the search algorithm returned a match for the same chemical composition with a HQI ≥ 0.7. No distinction was made between linear low density polyethylene (LLDPE), low density polyethylene (LDPE) and high density polyethylene (HDPE) due to the subtle differences in signature peaks between the three types of polyethylene and hence the greater risk of mislabelling a sample. Therefore, LLDPE, LDPE and HDPE were all classified as polyethylene.

An exception to only accepting polymers with a corresponding HQI ≥ 0.7 was made for foam pieces with spectra visually identified as that of polystyrene, but which had HQI < 0.7. Foam pieces were typically too small and fragile to clean to any useful extent and often broke apart by being clamped on to the FTIR spectrometer. To avoid polystyrene being underrepresented compared to the other plastics, foam pieces composed of polystyrene were included in the data analyses regardless of HQI value as long as the signature peaks



(a) "Native" plastic piece with biofilm



(b) Without biofilm

Figure 2.3: Spectra obtained by FTIR spectroscopy of the same plastic piece ingested by a northern fulmar (*Fulmarus glacialis*), demonstrating the masking effect of an outer layer of biofilm. The spectrum in red is the sample while the blue spectrum is the closest library match, as determined by the search algorithm. (a) shows the spectrum of a plastic piece prior to any cleaning or cutting. (b) shows the spectrum of the same piece of plastic after the surface layer was sliced off with a scalpel, clearly showing the signature peaks of polypropylene.

of polystyrene were identified in the spectra. This was the case in a total of 77 out of 160 samples (Faroe Islands: $n = 5$, Iceland: $n = 46$, Svalbard: $n = 23$, and Greenland: $n = 3$).

2.5 Statistics

Statistical analyses were performed using R version 3.5.2 (R Core Team, 2018).

The assumptions of normality and homogeneity were tested with the Shapiro-Wilk and F tests, respectively. The data failed to meet these assumptions both before and after log-transformation, hence non-parametric tests were used.

The percentage of fulmars with ingested plastics is termed the frequency of occurrence (FO). The binomial confidence interval using the Jeffrey's method was used when calculating the 95% confidence intervals for the frequency of occurrence of ingested plastic, as recommended by Provencher et al. (2017).

Furthermore, the mean, standard deviation, standard error of the mean, median and range of both mass and number of pieces presented are based on the entire set of fulmars, including those that had not ingested plastics.

The Wilcoxon rank sum test was used to test if there were differences in mass of industrial *versus* user plastics, as well as when comparing the different categories ingested by fulmars within the same region. The significance level was set at $p = 0.003$ after the Bonferroni correction to account for performing multiple comparisons.

Regional differences in ingested plastics were also tested with the Wilcoxon rank sum test. The significance level was set at $p = 0.008$ after the Bonferroni correction was applied.

In order to minimize the number of comparisons, only differences in mass were tested as it has been shown that the mass of plastics is more biologically relevant than number of pieces, and plastics disintegrate in the gut so using the mass provides a more accurate comparison (Provencher et al., 2017).

Differences between the regions with regards to polymer proportions were tested with the permutational multivariate analysis of variance using distance matrices by applying the `adonis2` function in the `vegan` package (Oksanen et al., 2019). Jung et al. (2018a) used the multiple response permutation procedure when examining differences in the polymer composition of ingested plastics by sea turtles. However, due to the considerable dispersion in the data sets for this study, the more robust test (`adonis2`) was used here, to minimize the risk of getting a significant model due to dispersion (Warton et al., 2011).

2.5.1 Pooling the Icelandic fulmars

The Wilcoxon rank sum test was used to compare the mass of ingested plastics between the Icelandic fulmars caught in 2013 and 2014. No significant differences were detected and the fulmars from the two years were hence pooled together to achieve a greater statistical power in the data analyses.

2.5.2 EcoQO

The Ecological Quality Objective (EcoQO) is a policy target set by the convention for the protection of the marine environment of the north-east Atlantic (OSPAR) commission. It states that fewer than 10% of fulmars should have more than 0.1 g of ingested plastics (OSPAR, 2008).

2.5.3 Comparison of polymer proportion by number and mass of plastics

Every individual piece of ingested plastic was weighed separately for the fulmars from north-east Greenland, thus facilitating a comparison of how the polymer profile differs between using mass and number of pieces to present the polymer proportions.

Chapter 3

Results

3.1 Ingested plastics

The results for the frequency of occurrence (FO) of ingested plastics are shown in Table 3.1 for the fulmars of all four regions.

Table 3.2 gives the descriptive statistics for the mass and number of pieces of ingested plastics by fulmars from the Faroe Islands and north-east Greenland. The descriptive statistics for the fulmars from Iceland and Svalbard are presented in Table 3.3 and have previously been reported (Trevail et al., 2015a; Trevail et al., 2015b); they are included here for the sake of completeness and ease of comparison. The metrics are reported both for industrial plastics (pellets), user plastics (sheet, thread, foam, fragment and other), as well as for the total plastic burden.

The summary statistics of the ingested plastics for the two individuals from Svalbard whose plastic pieces were analysed by FTIR spectroscopy in this study are presented in Table A.1 in Appendix A.

Table 3.1: The frequency of occurrence (FO) and 95% confidence interval (CI) of ingested plastics by northern fulmars (*Fulmarus glacialis*) by region. N represents the total sample size, whereas n is the number of individuals which had ingested plastic. The data on Svalbard and Iceland birds have previously been reported by Trevail et al. (2015a) and Trevail et al. (2015b), respectively.

Region	N	n	FO (%)	CI (%)
Faroe Islands	55	48	87.3	76.6 – 94.1
Iceland	40	36	90.0	78.0 – 96.5
Svalbard	40	35	87.5	74.8 – 95.1
Greenland	31	28	90.3	76.4 – 97.2

Table 3.2: Mass and number of pieces of ingested plastics by northern fulmars (*Fulmarus glacialis*) from Faroe Islands (FAE, $n = 55$ individuals) and north-east Greenland (NEG, $n = 31$ individuals). The summary statistics are given as mean ± standard deviation (SD), standard error of the mean (SEM), median and range. The maximum number in the range represents ingestion by a single individual.

		Mass (g)				Number of pieces			
		Mean ± SD	SEM	Median	Range	Mean ± SD	SEM	Median	Range
FAE	Total plastics	0.183 ± 0.23	0.031	0.098	0 – 1.190	11.4 ± 13.2	1.78	9	0 – 79
	Industrial	0.032 ± 0.05	0.007	0.002	0 – 0.198	1.36 ± 1.99	0.268	1	0 – 9
	User	0.151 ± 0.22	0.030	0.084	0 – 1.162	10.0 ± 12.7	1.71	6	0 – 77
	Sheet	0.003 ± 0.01	0.001	0	0 – 0.060	1.67 ± 9.02	1.22	0	0 – 67
	Thread	0.003 ± 0.01	0.002	0	0 – 0.087	0.64 ± 1.38	0.186	0	0 – 6
	Foam	0.007 ± 0.04	0.005	0	0 – 0.279	0.855 ± 2.07	0.279	0	0 – 11
	Fragment	0.137 ± 0.22	0.029	0.062	0 – 1.160	6.82 ± 7.31	0.985	5	0 – 36
	Other	0.002 ± 0.01	0.001	0	0 – 0.055	0.04 ± 0.19	0.026	0	0 – 1
NEG	Total plastics	0.058 ± 0.13	0.023	0.020	0 – 0.636	6.16 ± 8.29	1.49	3	0 – 39
	Industrial	0.007 ± 0.02	0.003	0	0 – 0.052	0.26 ± 0.58	0.103	0	0 – 2
	User	0.051 ± 0.12	0.021	0.011	0 – 0.584	5.90 ± 8.06	1.45	3	0 – 37
	Sheet	0.001 ± 0.004	0.0007	0	0 – 0.020	0.81 ± 2.04	0.366	0	0 – 11
	Thread	0.001 ± 0.001	0.0003	0	0 – 0.007	0.387 ± 0.62	0.111	0	0 – 2
	Foam	0.001 ± 0.003	0.0005	0	0 – 0.014	0.323 ± 1.45	0.260	0	0 – 8
	Fragment	0.042 ± 0.09	0.016	0.010	0 – 0.400	4.29 ± 6.17	1.11	2	0 – 25
	Other	0.006 ± 0.03	0.006	0	0 – 0.167	0.097 ± 0.40	0.071	0	0 – 2

Table 3.3: Mass and number of pieces of ingested plastics by northern fulmars (*Fulmarus glacialis*) from Iceland (ICE, n = 40 individuals) and Svalbard (SVA, n = 40 individuals). The summary statistics are given as mean ± standard deviation (SD), standard error of the mean (SEM), median and range. The maximum number in the range represents ingestion by a single individual. The data have been reported previously by Trevail et al. (2015a) and Trevail et al. (2015b).

		Mass (g)				Number of pieces			
		Mean ± SD	SEM	Median	Range	Mean ± SD	SEM	Median	Range
ICE	Total plastics	0.126 ± 0.14	0.022	0.085	0 – 0.575	15.5 ± 23.2	3.68	9	0 – 107
	Industrial	0.012 ± 0.03	0.005	0	0 – 0.128	0.50 ± 1.11	0.175	0	0 – 5
	User	0.113 ± 0.14	0.021	0.066	0 – 0.575	15.0 ± 22.9	3.63	8.5	0 – 104
	Sheet	0.002 ± 0.003	0.0005	0	0 – 0.016	1.13 ± 2.21	0.349	0	0 – 12
	Thread	0.003 ± 0.006	0.0009	0	0 – 0.023	0.93 ± 1.79	0.283	0	0 – 8
	Foam	0.012 ± 0.04	0.007	0	0 – 0.236	2.88 ± 8.91	1.41	0	0 – 43
	Fragment	0.092 ± 0.13	0.020	0.049	0 – 0.574	9.95 ± 17.1	2.70	4	0 – 100
	Other	0.005 ± 0.02	0.003	0	0 – 0.111	0.10 ± 0.30	0.048	0	0 – 1
SVA	Total plastics	0.080 ± 0.12	0.019	0.032	0 – 0.499	15.3 ± 34.7	5.49	5	0 – 200
	Industrial	0.006 ± 0.01	0.002	0	0 – 0.051	0.45 ± 0.96	0.151	0	0 – 5
	User	0.074 ± 0.12	0.019	0.022	0 – 0.490	14.9 ± 34.2	5.41	4.5	0 – 198
	Sheet	0.003 ± 0.01	0.002	0	0 – 0.071	1.53 ± 3.36	0.531	0	0 – 16
	Thread	0.018 ± 0.06	0.009	0	0 – 0.318	1.90 ± 3.83	0.605	0	0 – 18
	Foam	0.0004 ± 0.002	0.0003	0	0 – 0.008	0.68 ± 2.87	0.454	0	0 – 16
	Fragment	0.050 ± 0.10	0.015	0.016	0 – 0.480	10.7 ± 29.1	4.60	3	0 – 174
	Other	0.003 ± 0.01	0.002	0	0 – 0.082	0.05 ± 0.22	0.035	0	0 – 1

Faroe Islands

As discussed in Section 2.1.1, it is likely that plastics ingested by the Faroese fulmars were lost during the handling of the birds after capture. Therefore it is not appropriate to compare the different types of plastics against each other for these fulmars.

Iceland

The fulmars from Iceland had ingested significantly more user plastics compared to industrial plastics (Wilcoxon rank sum test, $p < 0.0001$). The average fulmar had ingested 0.113 g of user-type plastics and 0.012 g of industrial pellets. Furthermore, the fulmars had ingested significantly more fragment-type plastics compared to pellets, sheets, threads, foam and "other"-type plastics (Wilcoxon rank sum test, $p < 0.0001$ for all five tests).

Svalbard

Results for the analysis of the stomach plastics content of the fulmars from Svalbard are reported in Trevail et al. (2015a). As Trevail and co-authors did not specifically investigate the difference in user and industrial plastics, that was done here.

The fulmars from Svalbard had ingested a mean of 0.074 g of user-type plastics, which was significantly more than the 0.012 g of industrial pellets ingested by the average bird (Wilcoxon rank sum test, $p < 0.0001$). Moreover, they had ingested significantly more fragment-type plastics compared to the five other categories of plastics (Wilcoxon rank sum test, $p < 0.0001$ for all five tests).

Greenland

The fulmars from north-east Greenland had ingested significantly more user-type plastics compared to industrial plastics (Wilcoxon rank sum test, $p < 0.0001$). The fulmars had ingested 0.051 g of user plastics on average, compared to 0.007 g of industrial pellets. Additionally, the birds had ingested significantly more fragments by mass compared to all other categories (Wilcoxon rank sum test, $p < 0.0001$ for all five tests).

3.1.1 Comparison of regions

Figure 3.1a shows the mean mass and standard error of ingested plastics per fulmar for the four regions. The data from Svalbard and Iceland fulmars are from Trevail et al. (2015a) and Trevail et al. (2015b), respectively. Note that the values used for the Svalbard birds are based on the full data set of 40 fulmars.

The fulmars from the Faroe Islands had ingested significantly more plastics by weight than the fulmars from Svalbard and north-east Greenland (Wilcoxon rank sum test, $p = 0.006$ and $p = 0.0005$, respectively). The Icelandic fulmars had a significantly heavier plastic burden than the Greenlandic fulmars (Wilcoxon rank sum test, $p = 0.004$).

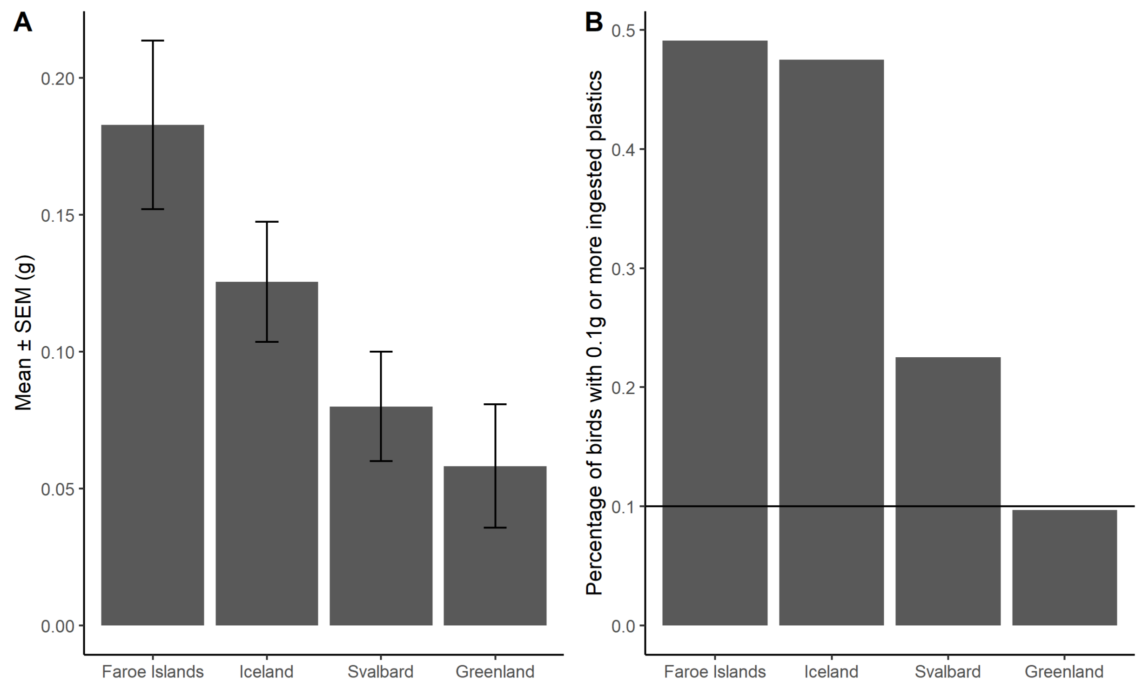


Figure 3.1: Plastic ingestion by northern fulmars (*Fulmarus glacialis*). (**A**) shows the mean ingestion of plastics in gram with error bars representing the standard error of the mean (SEM). (**B**) shows fulmars which had ingested $\geq$ 0.1 g of plastic. The horizontal bar represents the Ecological Quality Objective (EcoQO) set by OSPAR, stating that less than 10% of fulmars should have ingested $\geq$ 0.1 g of plastic. The data comes from fulmars caught in the Faroe Islands (2017, $n = 55$), Iceland (2013 and 2014, $n = 40$), Svalbard (2013, $n = 40$) and north-east Greenland (2017, $n = 31$). The data on fulmars from Svalbard and Iceland are from Trevail et al. (2015a) and Trevail et al. (2015b), respectively.

Similarly, the Faroese and Icelandic fulmars had ingested significantly more user plastics compared to fulmars from north-east Greenland (Wilcoxon rank sum test, $p = 0.0005$ and $p = 0.002$, respectively).

The fulmars from the Faroe Islands also had significantly heavier burdens of industrial pellets compared to fulmars from the three other regions (Wilcoxon rank sum test, $p = 0.004$, $p = 0.0005$ and $p = 0.002$ for Iceland, Svalbard and north-east Greenland, respectively).

Finally, the Faroese fulmars had ingested significantly more fragment-type plastics compared to fulmars from Svalbard and north-east Greenland (Wilcoxon rank sum test, $p = 0.003$ and $p = 0.002$, respectively). And the fulmars from Iceland had ingested significantly more fragments, by weight, than the birds from north-east Greenland (Wilcoxon rank sum test, $p = 0.006$).

Figure 3.1b shows the percentage of birds which had ingested $\geq$ 0.1 g of plastics per region. Fulmars from the Faroe Islands, Iceland and Svalbard all exceeded the EcoQO at 49.1%, 47.5% and 22.5% respectively, whereas the fulmars from north-east Greenland were just below the 10% threshold at 9.68%.

3.1.2 Origin of plastics

In addition to industrial pellets and user plastics (sheet, thread, foam and fragment), fulmars from all four regions had ingested plastics categorised as “other” (Tables 3.2, 3.3).

Two Faroese fulmars and one of the two Svalbard fulmars had ingested rubbery “other”-type plastics with unknown origin (Figure 3.2a, 3.2b, 3.2c).

Four fulmars from Iceland had ingested “other”-type plastic, seen in Figure 3.3. The pieces have been labelled as a bullet from a BB gun (Figure 3.3a), a lid (Figure 3.3b), a piece of synthetic fish bait (Figure 3.3c) and a bead (Figure 3.3d).

Of the Greenlandic fulmars, two had ingested plastics categorised as “other”. The first bird had ingested a clothes tag (Figure 3.2d). The second bird, shown in Figure 3.2e, had also ingested a clothes tag in addition to what appears to be a biocarrier.

3.2 Polymer identity

Polyethylene (PE), polypropylene (PP) and polystyrene (PS) made up the majority of plastic pieces ingested by fulmars from all four regions (Figure 3.4).

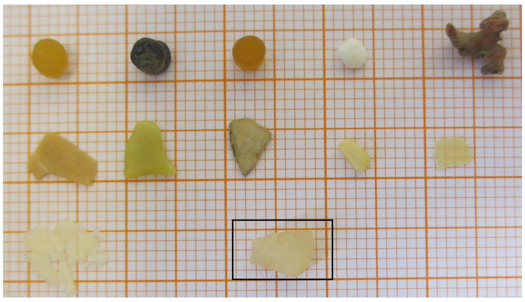
For the Faroese fulmars, 66.5% of the ingested plastic pieces were PE, 26.5% were PP and 6.01% were PS. The remaining 1% were made up of two pieces of polyamide (PA), two pieces of polyurethane (PU), one rubber piece and one cellulose particle.

The stomach plastic content for the Icelandic fulmars was also predominantly made up of PE (58.7%) followed by PP (21.5%) and PS (18.8%). For the remaining 1% of pieces, two were identified as PA, two as cellulose, one as acrylonitrile butadiene styrene (ABS) and one as polyethylene terephthalate (PET).

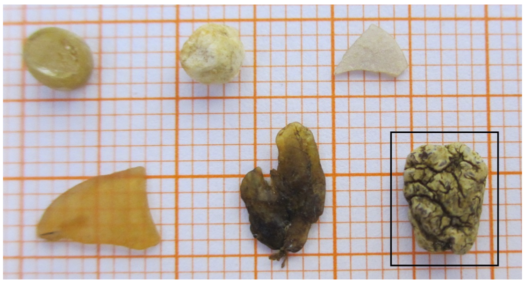
The two birds from Svalbard had ingested 70.7% PE, 17.7% PP and 11.2% PS. Only one piece was identified as PA, accounting for less than 1% of the pieces with Hit Quality Index (HQI) ≥ 0.70.

Finally, for the fulmars from Greenland, 61.9% of the ingested plastic pieces were PE, 31.2% were PP and 6.36% were PS. Only one piece was identified as a different polymer, namely PA accounting for less than 1% of the pieces with HQI ≥ 0.70.

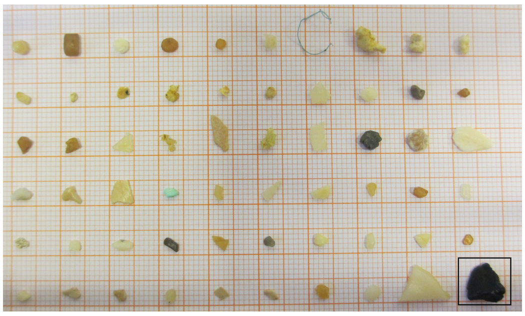
There was a statistically significant difference in the proportions of polymers between the four regions (permutational multivariate analysis of variance using distance matrices, $p = 0.001$). Fulmars from Iceland had ingested more pieces composed of PS than the fulmars from the other three regions (Figure 3.4). Similarly, PP made up a larger part of the total polymer profile for fulmars from north-east Greenland compared to fulmars from Svalbard in particular, but also compared to the Faroese and Icelandic fulmars. The contribution of PE to the make-up of the polymers was relatively stable across the regions, with the lowest recorded for Iceland and the highest for Svalbard.



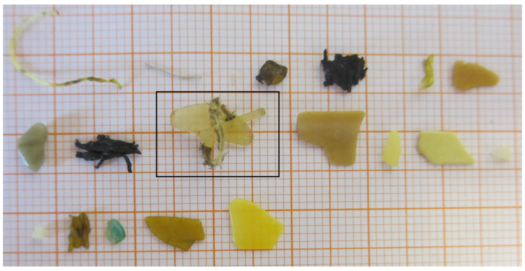
(a) FAE-008



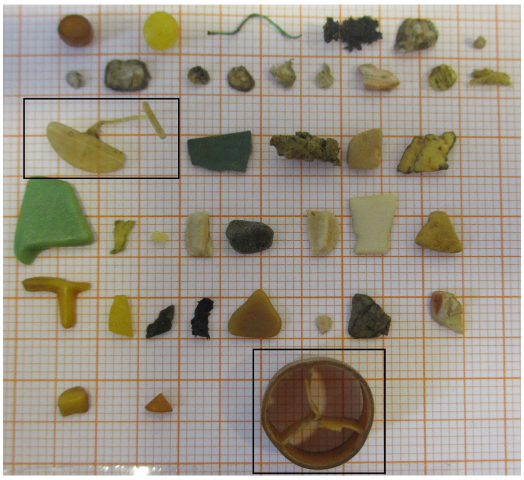
(b) FAE-014



(c) SVA-029

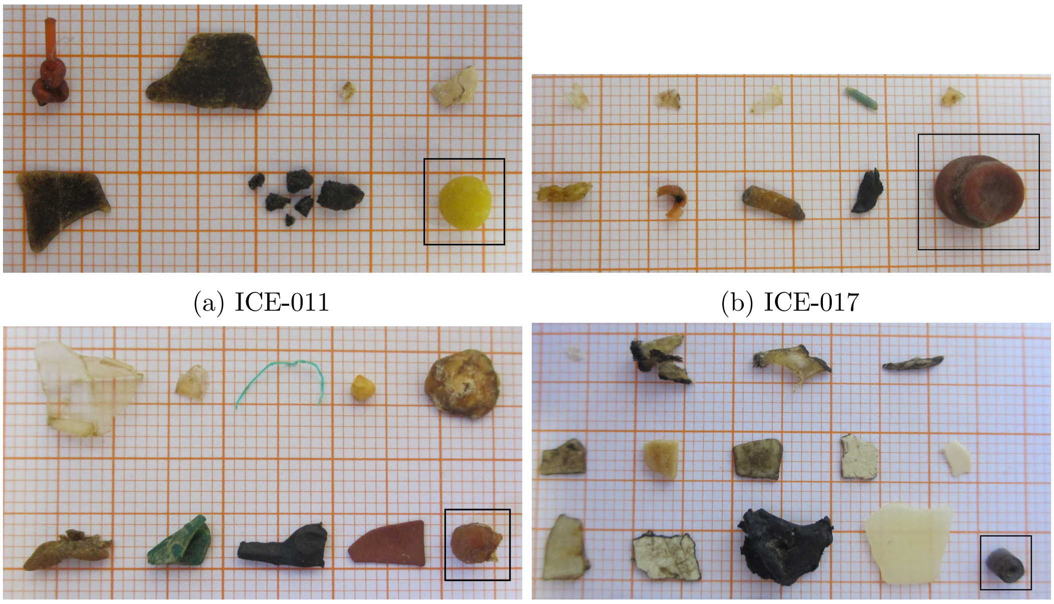


(d) NEG-002



(e) NEG-009

Figure 3.2: Total stomach plastic content of five northern fulmars (*Fulmarus glacialis*) from the Faroe Islands (FAE), Svalbard (SVA) and north-east Greenland (NEG). The pieces in the black squares have been categorised as “other”.



(a) ICE-011 (b) ICE-017

(c) ICE-027 (d) ICE-031

Figure 3.3: Total stomach plastic content of four northern fulmars (*Fulmarus glacialis*) from Iceland, 2013. The pieces in the black squares have been categorised as “other”, and appear to be a bullet from a BB gun, a lid, a piece of synthetic fish bait and a bead.

As seen in Figure 3.5, foam-type plastics were predominantly composed of PS, but two pieces of foam ingested by Faroese fulmars (Fig. 3.5a) were composed of PU. Icelandic fulmars (Fig. 3.5b) had also ingested PP foam in addition to PS foam pieces.

Polyethylene accounted for roughly 75% of the fragment-type pieces for all four regions, with the rest being mostly composed of PP. However, one fragment was identified as PA and two fragments were composed of cellulose for the Faroe Islands data set. The fulmars from Iceland had also ingested two cellulose fragments as well as one fragment of ABS. The data set from Svalbard (Fig. 3.5d) and north-east Greenland (Fig. 3.5c) included one fragment of PA each.

The “other”-type plastics in Iceland and north-east Greenland were exclusively composed of PP.

Pellets ingested by fulmars from north-east Greenland were exclusively composed of PE. The two birds from Svalbard had ingested pellets where *circa* 75% were PE and the rest PP. The majority of the pellets ingested by Faroese and Icelandic fulmars were also PE, but PP and PS pellets were also identified.

Apart from one PA sheet-type plastic ingested by Faroese fulmars, all sheets were composed of either PE or PP, with the dominant polymer changing from region to region. In the Faroe Islands, sheet-type plastics were predominantly composed of PE, but in Iceland and Svalbard, the majority of the sheets were PP. In north-east Greenland, the sheets were

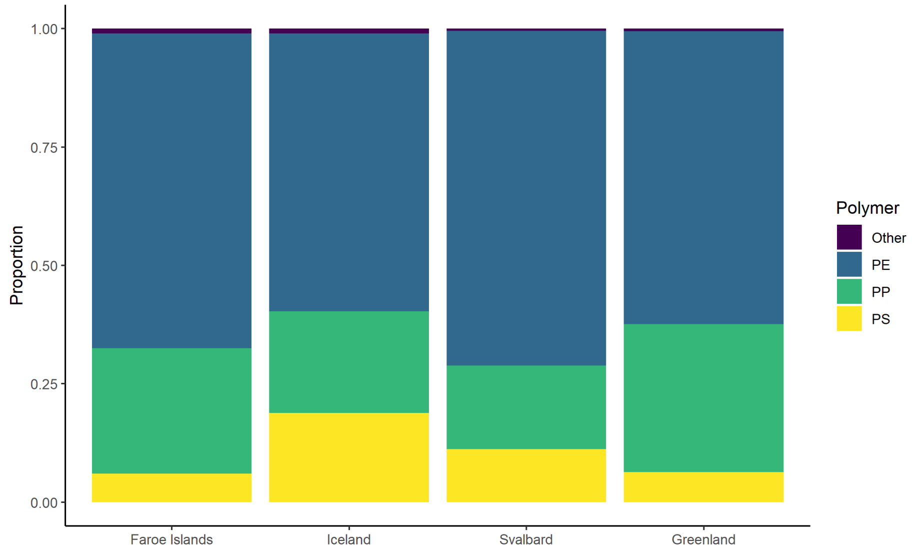


Figure 3.4: The proportion of polyethylene (PE), polypropylene (PP), polystyrene (PS) and other polymers ingested by northern fulmars (*Fulmarus glacialis*) from the Faroe Islands (n = 582 pieces), Iceland (n = 595 pieces), Svalbard (n = 232 pieces) and north-east Greenland (n = 173 pieces). The polymers labelled as "other" comprise polyamide, polyurethane, acrylonitrile butadiene styrene, polyethylene terephthalate and cellulose.

composed evenly of PE and PP.

Threads ingested by the fulmars from Svalbard were exclusively composed of PP. Polypropylene was the dominant polymer in thread-like plastics from the other three regions as well, with PE being the second most common polymer of threads. One fulmar from Iceland had ingested a piece of thread identified as PET.

Finally, fulmars from the Faroe Islands and Iceland had ingested threadballs. The two threadballs ingested by Faroese fulmars were both composed of PP. Two threadballs ingested by Icelandic fulmars were also PP, with the third being composed of PA.

Comparison of polymer proportion by number and mass of plastics

Figure 3.6 shows the difference in calculating polymer proportions based on the number of pieces (Fig. 3.6a) and on the mass of the pieces (Fig. 3.6b). When using the number of pieces in the calculation, the percentages are 61.9% PE, 31.2% PP, 6.36% PS and 0.58% PA. This changed to 69.7% PE, 27.3% PP, 2.87% PS and 0.10% PA when using weight instead. Note that the percentage of PA was too small to show on the graph when using proportion by mass (Fig. 3.6b).

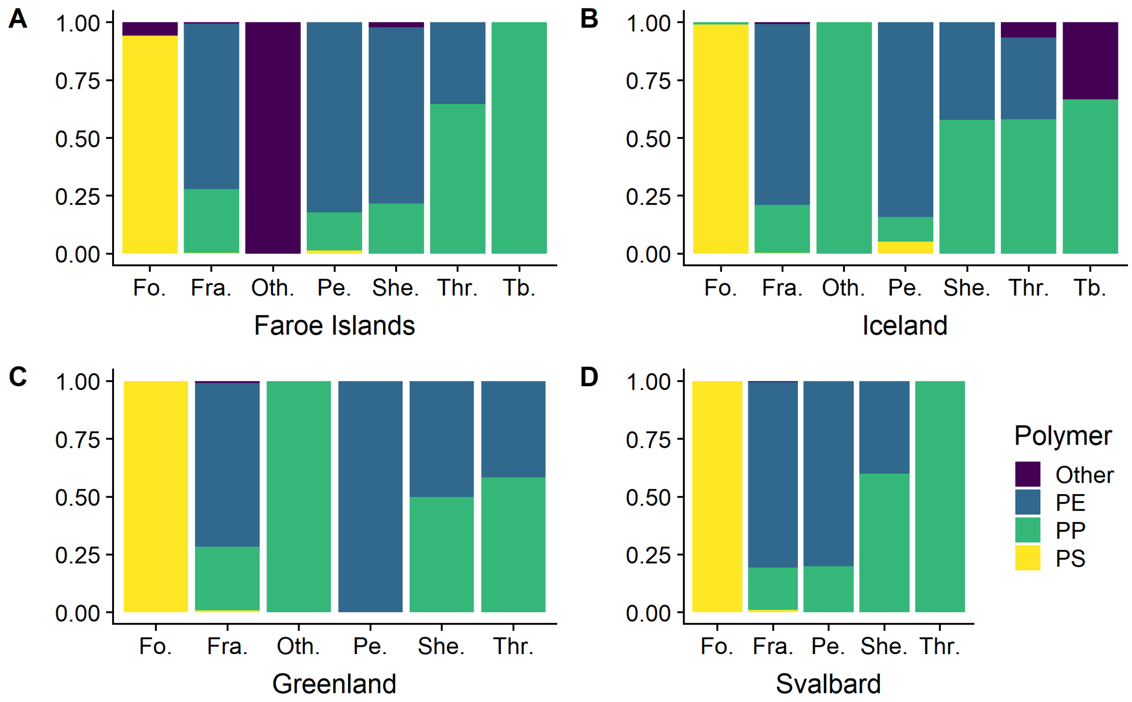


Figure 3.5: The proportion of polyethylene (PE), polypropylene (PP), polystyrene (PS) and other polymers by the type of plastic ingested by northern fulmars (*Fulmarus glacialis*) from the Faroe Islands (n = 582 pieces), Iceland (n = 595 pieces), Svalbard (n = 232 pieces) and north-east Greenland (n = 173 pieces). The polymers labelled as "other" comprise polyamide, polyurethane, acrylonitrile butadiene styrene, polyethylene terephthalate and cellulose. Fo = Foam; Fra = Fragment; Oth = Other; Pe = Pellet; She = Sheet; Thr = Thread; Tb = Threadball.

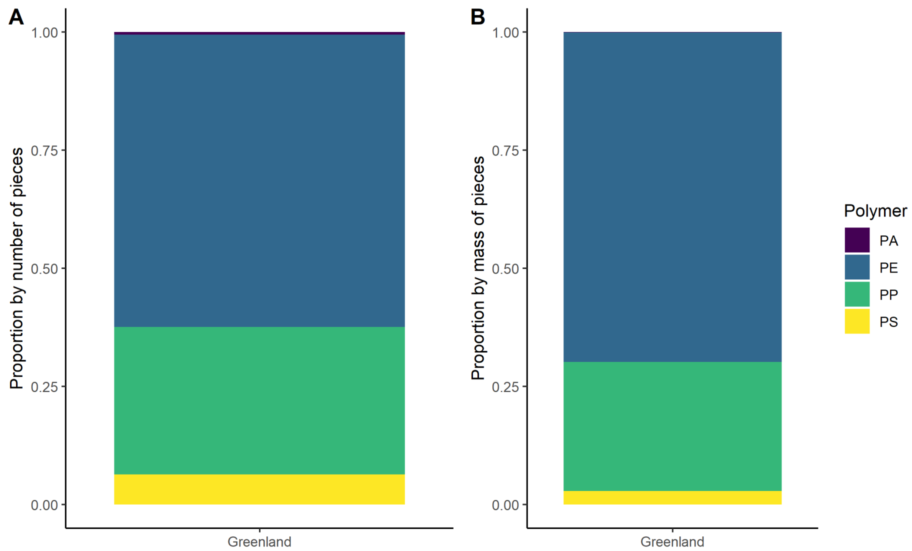


Figure 3.6: The proportion of polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyamide (PA) based on (**A**) the number of ingested plastic pieces and, (**B**) the mass of the pieces. The proportion of PA by mass was only 0.10%, and despite being present, it does not show in **B**. The plastic was ingested by northern fulmars (*Fulmarus glacialis*) from north-east Greenland ($n = 173$ pieces, total weight: 1806 mg).

Chapter 4

Discussion

4.1 Ingested plastics

This study found a high frequency of occurrence (FO) of ingested plastics in fulmars from the Faroe Islands and north-east Greenland. The fulmars from Iceland and Svalbard also had high FOs, as previously reported by Trevail et al. (2015a) and Trevail et al. (2015b).

Interestingly, the FO of ingested plastics is comparable between the four regions, even when taking the 95% CI into account. The Faroe Islands and Iceland are located at lower latitudes than the two arctic locations and are in closer proximity to large centres of human populations. Based on this, a difference in FO would be expected, with fulmars from the Arctic having more individuals with no ingested plastics. Fulmars from the Canadian Arctic do show a lower FO, at 31% for birds caught in 2003 – 2004 and 36% for birds caught in 2002 (Mallory, 2008; Mallory et al., 2006). However, more recent studies from the Canadian Arctic report an increased FO for birds captured in 2008 (84% and 80%) and 2013 (89%) (Poon et al., 2017; Provencher et al., 2009).

Nonetheless, despite having a similar FO of ingested plastics, the Faroese fulmars had ingested a significantly higher mass of plastics than the fulmars from Svalbard and north-east Greenland. However, this might be partially due to the fact that the Faroese fulmars were fledglings caught soon after leaving the nest. Previous research has shown that juveniles ingest greater quantities of plastics compared to older individuals (Avery-Gomm et al., 2012; Franeker et al., 2002). Furthermore, the stomach contents of the Faroese fledglings likely reflect parental transfer of plastics as well (Acampora et al., 2017). While there is no consensus yet for how long the residence time of plastics is in the gastrointestinal tract of fulmars, Franeker et al. (2015) estimate that 75% of hard plastics is eliminated within a month with a faster turnover for softer plastics. Therefore, some of the stomach plastic content for the Faroese fulmars has likely been transferred from the parents.

Another potential issue is the four year gap between the Svalbard fulmars caught in 2013 to the Faroe Islands fulmars caught in 2017. The production of plastics increased during this time (PlasticsEurope, 2018) and thus the level of marine plastic pollution likely increased as well. Indeed, Donnelly-Greenan et al. (2014) found that plastics ingestion by fulmars from the Pacific Ocean had increased significantly from 2003 to 2007. On the other hand, the fulmars from Iceland were caught in 2013 and 2014; and the north-east Greenland birds were caught in 2017. Yet the fulmars from Iceland had still ingested significantly higher levels of plastic than the birds from north-east Greenland.

Therefore, even though it is not an ideal comparison with regards to the differences in age and year, the fulmars from lower latitudes do appear to have ingested greater quantities of plastics than the arctic fulmars. This is also in accordance with previous results (Avery-Gomm et al., 2012; Avery-Gomm et al., 2018; Trevail et al., 2015a).

Type of plastics

This study found that fulmars from Iceland, Svalbard and north-east Greenland had ingested significantly greater levels of user plastics (sheet, thread, foam, fragment and other) compared to industrial plastics (pellet). This is in line with previous research on the composition of plastics ingested by fulmars (Avery-Gomm et al., 2012; Avery-Gomm et al., 2018; Bond et al., 2014; Kühn et al., 2012; Mallory, 2008; Mallory et al., 2006; Provencher et al., 2009; Terepocki et al., 2017). The Faroese fulmars were not included in this analysis due to the squeezed and torn stomachs.

The Faroese fulmars were included when assessing regional differences, and were found to have ingested significantly more pellets than the birds from the three other regions. This likely reflects the geographical position of the Faroe Islands, as it is closer to major industrial areas where production of plastics occur. Indeed, fulmars found beached in the Netherlands had ingested approximately 0.05 g pellets on average (Franeker et al., 2011), compared to the mean mass of 0.03 g pellets for the Faroese fulmars in the current study (Table 3.2), thus indicating that the amount of ingested pellets increases with proximity to large centers of human population.

Ascertaining the origin of the ingested plastics is highly important, but at the same time also exceedingly difficult to do. The weathering of the plastics in the environment and further wear whilst in the gut of animals, usually make the pieces impossible to identify. However, in this study it was found that fulmars from Iceland had ingested a bullet from a BB gun, a lid, a piece of rubber believed to come from synthetic fish bait and a bead. The bullet, at least, likely entered the ocean by being swept from land by rain or wind. Most strikingly, perhaps, were the two fulmars from north-east Greenland which had ingested two clothes tags and a biocarrier. Although near impossible to say, the clothes tags may have ended up in the ocean through an improperly managed landfill or discarded by people. However, both tags were intact and it seems unlikely that someone bought garments and tore the tag out of the textile which would lead to a tear in the fabric. This, combined with the fact that two fulmars from the same region had ingested tags, may indicate that a shipment of tags were discarded or lost. The biocarrier, if indeed it is one, probably derives from a wastewater treatment plant.

EcoQO performance

The ecological quality objective (EcoQO) is a target set by OSPAR (2008), stating that less than 10% of fulmars should have ingested 0.1 g or more of plastics. In this study, the fulmars from the Faroe Islands, Iceland and Svalbard all exceeded the EcoQO target (by 49.1%, 47.5% and 22.5%, respectively) and the birds from north-east Greenland were just below the 10% target.

Interestingly, Kühn et al. (2012) reported that 28% of Icelandic fulmars caught in 2011 exceeded the EcoQO target, compared to almost 50% for the birds from Iceland in the current study. This is a dramatic increase in fulmars exceeding the EcoQO in just two years. The fulmars were caught in the same area for both studies, hence excluding a spatial effect. The percentage of non-adults was higher in the current study (58%) compared to only 16% non-adults of the fulmars caught in 2011 (Kühn et al., 2012). Thus, one possible explanation for the rapid deterioration of EcoQO performance is that juvenile fulmars ingest greater quantities of plastics, which has been reported by other studies as mentioned above (Avery-Gomm et al., 2012; Franeker et al., 2002). In all likelihood, the explanation is a combination of several factors, including the age composition of the sampled fulmars, increased marine plastic pollution over time and the possible influence of random events such as shipping accidents suddenly releasing large amounts of plastics into the marine environment (Ebbesmeyer et al., 1994).

The poor EcoQO performance reflects the extent and ubiquity of marine plastics, particularly around the Faroe Islands and Iceland. Furthermore, it highlights the spatial gradient of ingested plastics, where fulmars captured at lower latitudes tend to have ingested more plastics compared to those caught in the Arctic. This trend is also observed when comparing the EcoQO performance reported in the scientific literature, where fulmars caught at low latitudes tend to exceed the EcoQO more often than fulmars from the Arctic (Avery-Gomm et al., 2012; Avery-Gomm et al., 2018; Bond et al., 2014; Provencher et al., 2009).

4.2 Polymer profile

In descending order, polyethylene (PE), polypropylene (PP) and polystyrene (PS) were the dominant polymers ingested by fulmars in all four regions. This reflects the demand and production of plastic polymers in Europe, where approximately 15 million tons of PE, 10 million tons of PP and 2 million tons of PS were produced in 2017 (PlasticsEurope, 2018). PE and PP were in highest demand, followed by polyvinyl chloride (PVC), PU and PET, with PS in sixth place. While two pieces were identified as PU and one as PET in the current study, PVC, PU and PET all sink in seawater (Richard et al., 2011) and are thus not frequently ingested by fulmars. How the pieces of PU and PET were ingested by the fulmars in this study is unknown. One possibility is that they had been ingested by prey which the fulmars subsequently ate. Indeed, Lefebvre et al. (2019) found that PET was the dominant polymer of ingested plastics in two species of fish (discussed below).

The scientific literature on the polymer composition of ingested plastic by fulmars – and wildlife in general – is scarce. As far as the author is aware, only one study has been published on the polymer composition of plastics ingested by fulmars (Tanaka et al., 2019). It examined plastics ingested by fulmar fledglings captured in the Faroe Islands in 2010, in addition to plastics regurgitated by laysan and black-footed albatrosses (*Diomedea immutabilis* and *Phoebastria nigripes*, respectively). For the fulmars, only 100 pieces each of fragments and pellets were examined by FTIR spectroscopy. For the fragments, 71% were identified as PE, 18% as PP, 1% each as PA and PET while the remaining 9% could not be assigned to a single polymer. For the pellets, 59% were PE, 21% PP, 2% ABS and 18% could not be assigned to a single polymer. These percentages are comparable to those reported in this study for the Faroese birds when taking the type of plastic into consideration (Figure 3.5a). Tanaka et al. (2019) combined the plastics for the laysan and black-footed albatrosses and found that 59% of the fragments were composed of PE, 32% of PP, 6% of PA and 3% of PS. Only one pellet was found which was composed of PP. Even though most of the PS in the current study was of the expanded polystyrene type (used to produce foam plastics), PS can also be used to manufacture hard plastics as seen for the albatrosses in Tanaka et al. (2019) and in the current study (Figure 3.5).

A study on different species of sea turtles from the central Pacific Ocean found that the majority of ingested plastics were PE followed by PP (Jung et al., 2018a), which is in line with the results presented in this study. On the other hand, plastics ingested by sardines (*Sardina pilchardus*) and anchovies (*Engraulis encrasicolus*) from the Mediterranean Sea were composed predominantly of PET followed by PE and PA (Lefebvre et al., 2019). This is similar to another study on sardines, anchovies and herring (*Clupea harengus*) from the Mediterranean Sea which found that the ingested plastics were composed of PE, PP and PET (Collard et al., 2015). However, their sample size was low with only 11 plastic pieces analysed.

PET sinks in seawater and it is therefore not surprising that it is frequently ingested by fish, but not fulmars which are surface-feeders. On the other hand, FTIR spectroscopy of ingested plastics by little auks from Newfoundland, Canada, revealed that the majority of the plastics were PE (77.6%) and PP (20.9%), with PET only accounting for 0.7% of ingested plastics together with nylon (Avery-Gomm et al., 2016). The little auk forages on zooplankton in the water column by diving down to 50 m (Anker-Nilssen et al., 2000) and, as such, would be expected to have a polymer profile with a greater representation of plastics made of negatively buoyant polymers. The reason for PE and PP still dominating the polymer profile for little auks might, then, be related to dimethyl sulfide (DMS), a so-called "infochemical".

Phytoplankton produce DMS, especially when grazed upon by zooplankton (Dacey et al., 1986). DMS is then utilized by seabirds as an olfactory foraging cue to locate areas with zooplankton; these areas have a correspondingly higher probability of presence of fish and other prey feeding on zooplankton (Nevitt et al., 1995). Savoca et al. (2016) found that virgin pieces of PE and PP were rapidly colonized by DMS-producing organisms when exposed to seawater. When they analysed the plastic pieces, they all emitted DMS and at sufficiently high concentrations for Procellariformes to detect. The biofouling of these plastic pieces occurred at the sea surface, in the photic zone, and could explain why the planktivorous little auk appears to have specifically selected for PE and PP which likely emitted the DMS foraging cue.

Many of the plastic pieces analysed in the current study were covered in a layer of biofilm, an example of which is shown in Figure 2.3. Thus, it is probable that a portion of the plastics ingested by the fulmars were emitting DMS, contributing to the ingestion.

Regional differences in polymer composition

There was a significant difference in the polymer proportions between the locations, as determined by permutational multivariate analysis of variance using distance matrices. Warton et al. (2011) argued that distance-based multivariate analyses can confound location and dispersion effects. Thus, in an effort to minimize the risk of this occurring, the current study employed a similar, but more robust statistical test than the multiresponse permutation procedure used by Jung et al. (2018a).

Icelandic fulmars ingested more PS compared to the birds from the other regions. Similarly, PP made up a larger portion of the plastic ingested by north-east Greenland fulmars, particularly when compared to the fulmars from Svalbard. The difference in the proportion of PP for the Greenlandic and Svalbard birds is interesting as some of the fulmars termed "Greenlandic" were caught closer to Svalbard than Greenland (the squares in Figure 2.1 indicate the sampling locations for the Greenlandic fulmars). As fulmars can travel long distances to forage, it is not inconceivable that some individuals included as Greenlandic fulmars actually belonged to the Svalbard population. Yet, there does appear to be a difference in the polymer composition between plastics ingested by Svalbard and Greenland fulmars.

Fulmars from the Faroe Islands had also ingested pieces identified as PA, PU, rubber and cellulose, accounting for 1% of polymers with a HQI ≥ 0.7. The Icelandic fulmars had ingested PA, cellulose, ABS and PET, also accounting for 1% of the included polymers. In contrast, one fulmar each from Svalbard and Greenland had ingested a piece of PA. The variety of polymers, therefore, seems to be greater for the fulmars from the comparatively low latitude regions, Faroe Islands and Iceland, compared to the Arctic fulmars, as hypothesized.

A comprehensive study investigating the type and origin of macro-plastics washed ashore on the coastline of Svalbard found that most of the plastics came from the Barents Sea fishing fleet (Falk-Andersson et al., 2019). Plastics on beaches around Svalbard have also been examined by infrared spectroscopy by Magerl (2019) who found that the majority of the plastics were PE followed by PP and PS, as was found in this study. Thus, it is reasonable to assume that the plastics ingested by the Svalbard fulmars reflect, in large part, pollution by fisheries in the region. It also demonstrates how the examination of macro-plastics (which subsequently disintegrate into pieces small enough for fulmars to ingest) can act in concert with studies on plastic ingestion by fulmars.

Fulmars migrate away from the breeding colonies to the open ocean during winter, and this could be a potential confounding factor as fulmars from different regions may have overlapping wintering areas. Depending on how long plastics are retained in the gastrointestinal system of fulmars, plastics recovered from birds caught at breeding sites could potentially represent marine debris from another region. However, previous research indicates that the residence time of ingested plastics is approximately one month (Franeker et al., 2015), and fulmars arrive at nesting grounds in late spring and were not captured until early to late autumn. Thus, the risk of the plastics recovered from the fulmars being from the wintering areas is minimal. Nevertheless, further research into the dynamics of ingested plastics by fulmars is warranted and will add another dimension to current monitoring efforts.

A limitation of the current study is that the polymer composition of ingested plastics by the Svalbard fulmars is only based on two individuals. And although the number of individual pieces is comparatively high, it is likely partially due to fragmentation within the gut and thus not truly representative of the ingestion by fulmars from the region. However, it helps provide compelling evidence that the polymer composition of ingested plastics should be the focus of future research.

Number *versus* mass of pieces

Basing the polymer proportions on the number of pieces of a given composition could lead to skewed or biased values. Plastic pieces disintegrate in the gut of the fulmars and a single ingested piece fragmenting into many smaller pieces may then lead to a bias towards a certain polymer. Indeed, reporting mass rather than number of pieces is recommended (Provencher et al., 2017).

The polymer proportions in the current study were based on number of pieces. This was largely a matter of time-constraint as over 1700 plastic pieces were included in the FTIR spectroscopy analysis. Nevertheless, the plastic pieces recovered from the north-east Greenland fulmars were weighed individually. A comparison of the polymer profile based on number and mass of pieces was then performed. While there were changes in the percentages of each polymer, on the whole, the differences were not large and did not affect the overall trend of PE being the predominant polymer ingested by fulmars, followed by PP and PS. Therefore, basing the polymer proportions on the number of pieces instead of mass was deemed acceptable in the current study. Nevertheless, further investigation of this is advised.

Chapter 5

Conclusion

The majority of the fulmars from all regions had ingested plastics, with similar frequency of occurrence of plastic ingestion across the four regions. The fulmars from the Faroe Islands had ingested significantly more plastics compared to the fulmars from Svalbard and north-east Greenland. Similarly, the fulmars from Iceland had ingested significantly greater mass of plastics than the fulmars from north-east Greenland. This is in line with the hypothesis that Arctic fulmars ingest less plastics than fulmars caught at lower latitudes. User-type plastics dominated the stomach plastic burden for fulmars from Iceland, Svalbard and north-east Greenland (the Faroese fulmars were not included in this comparison). A geographical effect in plastic ingestion was found for the levels of pellets, with Faroese fulmars having ingested significantly more pellets compared to the birds in the three other regions.

Overall, the EcoQO performance was poor, with nearly half of the examined fulmars from the Faroe Islands and Iceland having ingested 0.1 g or more of plastics. In keeping with the trend of Arctic fulmars ingesting less plastics, fewer fulmars from Svalbard and north-east Greenland had ingested ≥ 0.1 g plastics.

In all four regions, the majority of ingested plastics were composed of polyethylene followed by polypropylene and polystyrene. However, the proportions of the three polymers varied between the locations. There were also indications that there was a greater variation of polymers in the Faroe Islands and Iceland sets compared to those from the Arctic, in line with the hypothesis.

Future perspectives

Marine plastic pollution is likely only going to increase in scale and severity in the future, making investigating the dynamics and effects of marine plastics essential. Only with a thorough understanding of all aspects of marine plastic pollution will the development of effective and meaningful mitigation strategies be possible. This entails, then, an interdisciplinary effort—combining knowledge gained from natural and social sciences, engineering and humanities to address the issue.

This study has identified several areas – within the field of fulmars as bioindicators of marine plastic pollution – where further research efforts should be directed. For one, the dynamics of ingested plastics should be elucidated to obtain a robust estimate of the plastics' residence time in the GI tract. This will yield valuable information, aiding the understanding of which geographical area ingested plastics represents. Similarly to this, combining an investigation of ingested plastics, using emetics to avoid having to sacrifice the birds, with ongoing geo-locating studies tracking the spatial movement of fulmars would provide insight into which areas the plastics was picked up from. More studies need to be conducted on the polymer identity of ingested plastics by a range of animals, preferably with varying foraging strategies. FTIR spectroscopy can be prohibitively time-consuming, yet the information gained will add more depth to the understanding of marine plastic pollution. A more comprehensive study on geographic differences in the polymer composition of ingested plastics is warranted. Ideally greater sample sizes would be used, but the priority would be to increase the spatial coverage in addition to having all the fulmars caught during the same time period to avoid any temporal bias. However, many of the studies conducted on plastic ingestion by fulmars use either beached birds or victims of e.g., long-line fishing, and are thus constrained by opportunistic sampling.

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Appendix A

Descriptive statistics Svalbard fulmars

Table A.1: Plastics ingested by northern fulmars (*Fulmarus glacialis*) from Svalbard ($n = 2$) used in the FTIR spectroscopy analysis. These two fulmars are part of a larger dataset previously reported by Trevail et al. (2015a). The mean ± standard deviation (SD), standard error of the mean (SEM), median and range are presented both for the mass and number of pieces of plastics ingested. The maximum number in the range represents ingestion by a single individual.

	Mass (g)			
	Mean ± SD	SEM	Median	Range
Pellet	0.030 ± 0.03	0.021	0.030	0.009 – 0.051
Sheet	0.001 ± 0.002	0.001	0.001	0.0001 – 0.003
Thread	0.0001 ± 0.00	0.00	0.0001	0.0001 – 0.0001
Foam	0.008 ± 0.001	0.001	0.008	0.007 – 0.008
Fragment	0.381 ± 0.14	0.100	0.381	0.281 – 0.480
Other	0.041 ± 0.06	0.041	0.041	0 – 0.082
Total	0.461 ± 0.06	0.038	0.461	0.422 – 0.499
	Number of pieces			
Pellet	3.5 ± 2.12	1.5	3.5	2 – 5
Sheet	4 ± 4.24	3	4	1 – 7
Thread	1 ± 0.00	0.00	1	1 – 1
Foam	12.5 ± 4.95	3.5	12.5	9 – 16
Fragment	108.5 ± 92.6	65.5	108.5	43 – 174
Other	0.5 ± 0.71	0.5	0.5	0 – 1
Total	130 ± 99.0	70.0	130	60 – 200