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Plastic ingestion by Arctic fauna: A review

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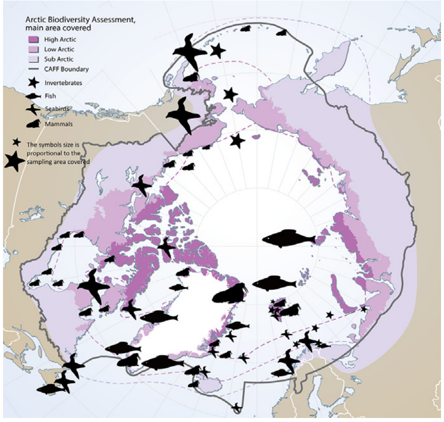
HIGHLIGHTS

- A standardization of methods is urgently needed.
- Additional baselines data are required to define species for biomonitoring.
- Plastic ingestion by biota in the Russian and European Arctic is overlooked.
- Ecotoxicological impacts of microplastics on Arctic organisms are poorly studied.

GRAPHICAL ABSTRACT



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ABSTRACT

The distribution of marine plastic litter is unequal around the world, some areas being more polluted. Given that the Arctic is not a highly populated area, very low levels of plastics are expected. However, the Arctic is not significantly less polluted than populated areas further south. Plastic has already been found in most compartments of the Arctic Ocean and climate change will likely exacerbate that issue due to sea ice melting and increasing maritime activities. The Arctic fauna is, and will be, increasingly exposed to the plastic pollution threat in the coming years and decades. The objective of this review is providing a summary of existing data, as well as perspectives and important knowledge gaps regarding plastic ingestion by Arctic fauna. Among other knowledge gaps, we highlighted the need for a species for biomonitoring of plastic pollution in the Arctic, i.e. the northern fulmar and/or the polar cod, for more data in fauna from the Russian and European Arctic and for experimental studies on impacts of plastic ingestion on Arctic species.

1. Introduction

Plastics are produced in huge quantities, reaching 368 million tonnes in 2019 (PlasticsEurope, 2020), and most of them are accumulating in the environment or in landfills (Geyer et al., 2017). The distribution of marine plastic litter is unequal around the world (Cózar et al., 2014), some areas are more polluted due to, for example, population density

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(Browne et al., 2011) or hydrodynamics (Moore et al., 2001; Cózar et al., 2017). Given that the Arctic is not a highly populated area, very low levels of plastics are expected. However, the Arctic is not significantly less polluted in plastic litter, including microplastics, than populated areas further south (Barrows et al., 2018; Halsband and Herzke, 2019).

Plastic levels in the Arctic are the result of local and global sources. Cózar et al. (2017) demonstrated that the poleward branch of the thermohaline circulation acts as a conveyor belt towards the Arctic Ocean, making it a sink for plastic debris. Subsurface currents may further transport significant amounts of plastics towards the polar regions (Wichmann et al., 2019). Air is also thought to be a long-distance transport medium (e.g. Dris et al., 2016). In addition to distant sources, both macro- (≥5 mm) and microplastic (<5 mm, MP) debris may also be released from local sources such as wastewater outlets, open disposal sites, tourism, fishing and shipping activities (Grøsvik et al., 2018; Granberg et al., 2019; Lebreton and Andrady, 2019; Eriksen et al., 2020). Similar to other regions of the world, fibres dominate in the shape of anthropogenic particles found in Arctic surface and subsurface water (Lusher et al., 2015), sea ice (Kanhai et al., 2020), sediment (Mu et al., 2019a), benthic invertebrates (Fang et al., 2018) and fish (Morgana et al., 2018). A modelling study predicted a maximum of more than 90,000 microfibres per cubic meter of water in the Arctic seas, which is much higher than in all other investigated oceanic regions (Lima et al., 2021). Wastewater is believed to be one of the main sources of fibres in the Arctic Ocean (Sundet et al., 2016; Kanhai et al., 2020). In the Arctic, wastewater is generally discharged directly into the environment, despite being a point source of plastics, and especially MPs (Murphy et al., 2016; Reed et al., 2018; Gatidou et al., 2019; von Friesen et al., 2020). For example, around 100 fibres per litre of wastewater are discharged into the Adventfjorden from Longyearbyen, Svalbard (Sundet et al., 2016).

Plastic levels in the Arctic are expected to increase as a consequence of climate change. Indeed, sea ice is known to contain macroplastics (Borgogno et al., 2019) and high loads of MPs (Peeken et al., 2018). The melting sea ice will first release high quantities of plastics into the surrounding water (Peeken et al., 2018) but a decrease in sea ice will also allow more tourism, fishing and shipping activities. Plastic has already been found in most compartments of the Arctic Ocean, i.e. sea ice, sediment, beaches and water, (Obbard et al., 2014; Kanhai et al., 2019; Falk-Andersson et al., 2019; Collard et al., 2021; Hänninen et al., 2021) and climate change will likely exacerbate that issue. The Arctic fauna is, and will be, increasingly exposed to the plastic pollution threat in the coming years and decades.

The consequences of plastic ingestion are not well-known, especially in Arctic marine organisms (Halsband and Herzke, 2019). Aquatic model species are usually chosen to study the impacts of plastic ingestion such as the fish species *Danio rerio* and *Pomatoschistus microps*, although some species, partly found in the Arctic, such as *Mytilus edulis* (Berge et al., 2005) are sometimes used (de Sá et al., 2018). Those studies, reviewed in de Sá et al. (2018), showed two different possible outcomes: either no impact (e.g. Rainieri et al., 2018) or negative impacts of plastic ingestion such as inflammation and lipid accumulation in liver (Lu et al., 2016), intestinal damage, oxidative stress (Lei et al., 2018), reduced acetylcholinesterase activity (Oliveira et al., 2013) or a decrease in the filtration rate (Woods et al., 2018). Arctic wildlife interacts with plastic both through entanglement and ingestion in the environment (Kühn et al., 2015). Few Arctic field studies showed such interactions, with a focus on fish and seabirds (e.g. Provencher et al., 2010; Kühn et al., 2018). Studies on other organisms do exist and showed plastic ingestion by lower and higher trophic levels: invertebrates such as *Pandalus borealis*, *Ophiura sarsii* or *Galathowenia oculata* (e.g. Fang et al., 2018; Knutsen et al., 2020) and marine mammals such as the polar bear *Ursus maritimus* or the beluga *Delphinapterus leucas* (Stimmelmayr et al., 2019; Moore et al., 2020), respectively.

This review aims at providing a summary of existing data, as well as perspectives and important knowledge gaps regarding plastic ingestion by Arctic fauna. We have adopted the Conservation of Arctic Flora and Fauna's (CAFF) definition of the Arctic (Fig. 1) and only sampling sites within those boundaries will be discussed. However, some studies on animals sampled in Newfoundland, Canada are also included in this review due to its proximity to the Arctic and because the species investigated there were also studied in other Arctic regions. We used the Web of Science database to look for relevant peer-reviewed articles by using several keyword combinations which always included "Plastic" and "Arctic". Next to those two keywords, we added "ingestion", "bird", "fish", "mammal", "invertebrates" and "fulmar". Those searches led to some irrelevant publications, dealing with methods or management for example. All search results were then manually checked in order to keep publications reporting plastic ingestion by Arctic fauna. We also checked references in relevant publications, as well as using our network of colleagues and collaborators, to find publications which would otherwise likely have been missed by the keyword searches. We did our utmost to include all the scientific and grey literature available online, though we did not use any search tool to cover the grey literature. The review structure is as follows: trophic levels of large groups of marine organisms from the lowest to the highest group (invertebrates, fish, seabirds, marine mammals), followed by terrestrial mammals, before we offer our perspectives and discuss knowledge gaps.

2. Invertebrates

To our knowledge, only four studies published in scientific journals have specifically focused on and reported MP ingestion by invertebrates in the Arctic and sub-Arctic (Fang et al., 2018; Iannilli et al., 2019; Knutsen et al., 2020; Fang et al., 2021). The first one sampled benthic invertebrates in the Bering and Chukchi Seas, including starfishes, shrimp, crab, brittle star, whelks and bivalves. Overall, the mean abundances of MPs in all the benthic organisms varied from 0.02 item/g wet weight (ww) to 0.46 item/g ww, which is lower than in benthic organisms in coastal areas and in the open ocean worldwide (Fang et al., 2018). Fibres were dominant as well as red and transparent particles. As expected, when fibres dominate, the most common polymers were polyamide, polyethylene and polyester. The most common size class was 0.10–1.50 mm (66%). Interestingly, the authors correlated the MP abundances with several seawater parameters and found a negative correlation between MP abundances and both water temperature and water depth. Moreover, a negative correlation was also found between MP abundances and MP sizes. Such investigations are needed to better understand how MP ingestion is influenced in small organisms living within a small area as invertebrates do. Later, MP abundances in surface sediment at the same sampling sites were reported (Mu et al., 2019a). Microplastic abundances differed between those two studies: in benthic organisms the abundances decreased from north to south while abundances in surface sediment showed a gaussian distribution (Fang et al., 2018; Mu et al., 2019a).

The second study reported MP ingestion by an amphipod species, *Gammarus setosus*, from Svalbard (Iannilli et al., 2019). Most of the MPs were fragments made of poly(methylacrylamide) (PMMA), a material commonly used in the marine industry. The PMMA fragments looked like paint flakes, probably coming from ships or naval equipment. Besides PMMA, polyacrylamide and polyamide fragments were also recorded. Those materials are believed to mostly come from fishing equipment (Iannilli et al., 2019), highlighting the threat that fishing industry may represent.

In 2020, Knutsen et al. (2020) investigated MP ingestion by polychaetes from the Barents Sea and the authors found MPs in both soft tissues and tubes of the polychaetes *Galathowenia* spp. and *Owenia borealis*. Overall, microplastic concentrations ranged between 48 ± 67 and 790 ± 1100 items/g ww (mean ± SD). Polypropylene (PP) and polyethylene terephthalate (PET) were the most common polymers. Similarly to Fang et al. (2018) and Mu et al. (2019a), Knutsen et al. (2020) reported a different MP composition in sediment and in

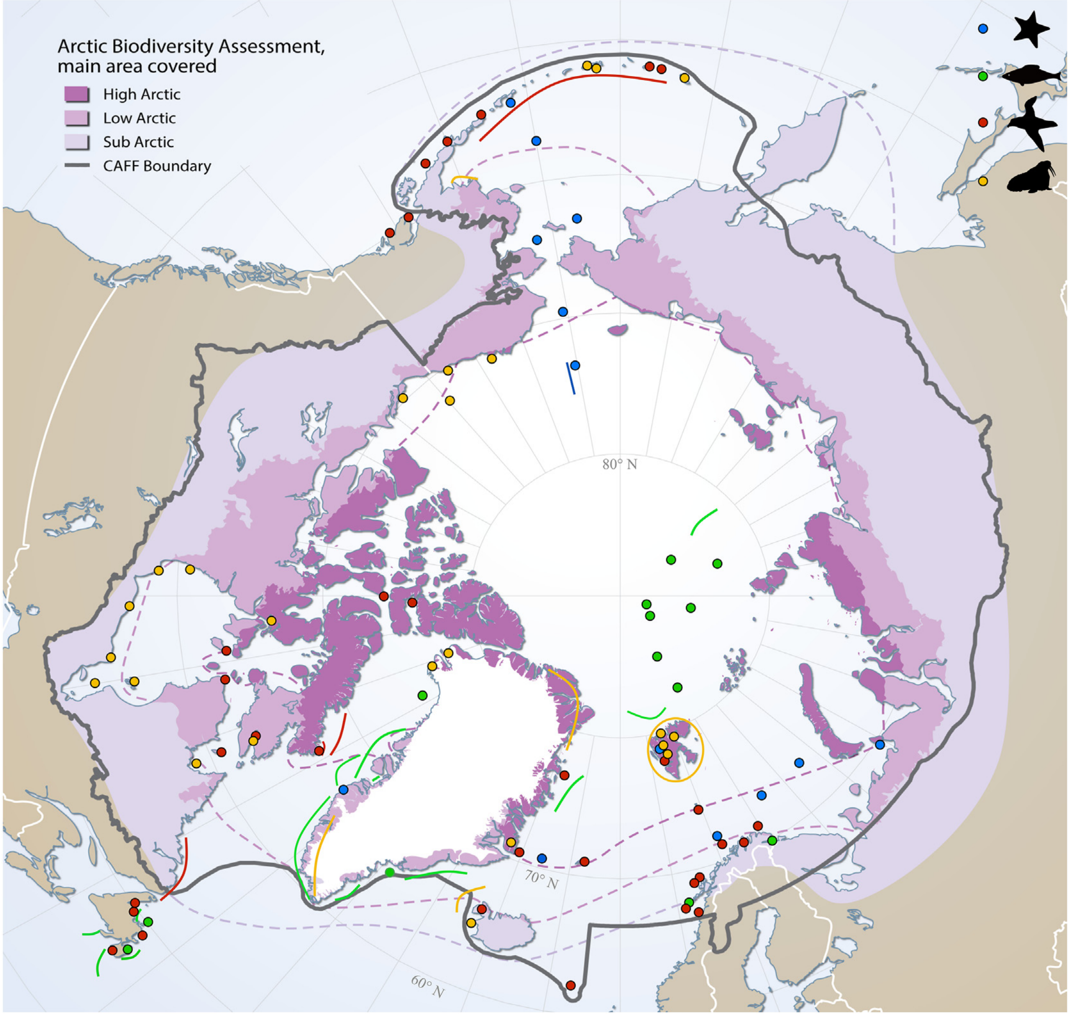

Fig. 1. Map of the Arctic region, as defined by CAFF, showing the sampling sites of Arctic fauna. Modified from Culp et al. (2012). Dots represent a single sampling site, lines represent several sampling sites within the same area and in the same study. Blue: invertebrates, green: fish, red: birds, orange: mammals. Some studies are not represented here because no precise sampling site was provided (e.g. Day, 1985; Finley, 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

polychaetes from the same sampling sites. This might be explained by a possible prey selection behaviour where several MP characteristics may influence the organism choice.

Finally, three benthic species or groups were collected in the Chukchi Sea, the anemones *Actiniidae*, the starfish *Ctenodiscus crispatus*, and the crab *Chionoecetes opilio* (Fang et al., 2021). Mean MP abundances ranged between 0.2 and 1.7, 0.1 to 1.4 and 0.0 to 0.6 item per individual, respectively. Many polymers were found but polyesters were the most common. The abundance of MPs ingested by sea anemones were significantly higher than in the starfish and the crabs. Sea anemones are opportunistic predators and feed on many different organisms. In that study, they are suggested to be an appropriate bioindicator of MP pollution compared to the two other studied organisms as they showed a spatial variability, which can be explained by the ocean currents (Fang et al., 2021).

In addition to scientific publications, several reports have investigated plastic ingestion in invertebrates. Bivalves were the main focus and, in some cases, showed a high level of ingested plastics (Lusher et al., 2017; Bråte et al., 2020; Granberg et al., 2020). *Mytilus* species collected in several countries had on average around 0.23 MP per individual (Bråte et al., 2020) while mussels from northern Norway showed higher levels: 2.8 MPs per individual (Lusher et al., 2017). Lusher et al. (2017) found a majority of fibres (almost 100%) in their Arctic samples while fragments dominated in the report from Bråte et al. (2020). This might be explained by a difference in the methodology, i.e. exclusion of some sampling sites with very low plastic levels, a higher Fourier-transform infrared (FTIR) spectroscopy coverage or a lower recovery rate for fibres compared to fragments, or in the prevention of contamination (Bråte et al., 2020). On the other hand, Iceland cockles (*Clinocardium ciliatum*), Iceland scallops (*Chlamys islandica*), and wrinkled rock-borers (*Hiatella arctica*) from Svalbard did not contain any MPs after blank-correction (Sundet et al., 2016, 2017). Likewise, the levels of plastics in the sediment samples taken at the same locations as the Iceland scallops and wrinkled rock-borers were lower than in the blank samples (Sundet et al., 2017). Blue mussels (*Mytilus spp.; n* = 10), however, which had been placed in cages at a floating dock in the harbour of Longyearbyen, Svalbard for 4 to 9 months contained, on average, 9.5 fibres per individual, after blank-correction. Nine of the ten blue mussels also contained fragments and spherical MPs (Sundet et al., 2016). The authors concluded that the spherical MPs originated from the local settlement of Longyearbyen. But they also detected high concentrations of fibres in the wastewater, which may be, at least partially, the source of the fibres detected in the blue mussels. Blue mussels (*Mytilus edulis*) sampled in Greenland showed a high average contamination level (2 ± 2 particles per individual) with a shape and colour diversity different than in sediment at the same sampling sites (Granberg et al., 2020).

Nearly 20% of snow crabs (*Chionoecetes opilio*) caught as part of the annual Norwegian-Russian ecosystem survey in the Barents Sea had ingested plastics between 2004 and 2013 (Sundet, 2014). Similarly, Gebruk et al. (2019) found that snow crabs, great spider crabs (*Hyas araneus*), and hermit crabs (*Pagurus pubescens*) from the Pechora Sea collected in 2017 had ingested plastics but more details, such as frequency of occurrence, are not listed. Fuhrmann et al. (2017) found plastic ingestion by red king crabs (*Paralithodes camtschaticus*) from Porsangerfjorden, Norway. Of 139 red king crabs caught in 2011–2012, 37.9% had ingested plastic, mostly in the form of fibres. These crab species are most likely predominantly exposed to plastics in sediments as one feeding behaviour is filtering sediment for prey (Fuhrmann et al., 2017).

3. Fish

Fish have been studied in different areas of the Arctic and several species were investigated: polar cod (*Boreogadus saida*), Atlantic cod (*Gadus morhua*), Greenland cod (*Gadus ogac*), bigeye sculpin (*Triglops nybelini*), Atlantic salmon (*Salmo salar*), Greenland shark (*Somniosus microcephalus*) and capelin (*Mallotus villosus*) (Leclerc et al., 2012; Nielsen et al., 2014; Bråte et al., 2016; Liboiron et al., 2016; Kühn et al., 2018; Morgana et al., 2018; Liboiron et al., 2019; Saturno et al., 2020; Granberg et al., 2020) (Table 1, Fig. 2). The frequency of plastic occurrence ranged from 0% to 34%. The Atlantic cod was the most studied species, and plastics were reported in 0% of fish from the Norwegian coast (Bråte et al., 2016), and in 2.4% (Liboiron et al., 2016), 1.7% (Liboiron et al., 2019) and 1.4% (Saturno et al., 2020) of fish from Newfoundland, Canada. These results are consistent with another study which investigated plastic contamination in Atlantic cod from the Baltic Sea (Rummel et al., 2016). Overall, all studies reported a low contamination level in the Atlantic cod. This low ingestion level might be explained by the influence of environmental and biological factors (Liboiron et al., 2016) or by a possible underestimation of the number of plastics. Indeed, Bråte et al. (2016) extracted plastic-like particles through a visual assessment, which prevents an investigation of smaller MPs, while the three Canadian studies used a threshold of 1 mm. Any particles smaller than one millimetre were then overlooked although, in some abiotic compartments, they are by far the most common size class (Bergmann et al., 2017; Peeken et al., 2018). Within the Gadidae family, two other species have been studied: the polar cod (Kühn et al., 2018; Morgana et al., 2018) and the Greenland cod (Granberg et al., 2020), with different results. Eighteen percent of polar cods were found to have ingested plastic in Greenland (Morgana et al., 2018) while, around Svalbard, 2.8% had plastic in their stomach (Kühn et al., 2018). By contrast, all investigated Greenland cods were found to have ingested plastic ($n = 9$, Granberg et al., 2020). Those cods were caught in western Greenland and the highest average number of plastic particles was found in individuals collected close to MP sources, i.e. a wastewater outlet and a dumping site.

Considering all three cod species investigated, various polymers were found: polycyclohexylene-dimethylene terephthalate (PCT), polyethylene (PE), polyvinylchloride (PVC), polyethylene terephthalate (PET) and rubber, among others, as well as various sizes and colours (Bråte et al., 2016; Morgana et al., 2018; Liboiron et al., 2019; Granberg et al., 2020). This highlights the variety of plastic debris in the Arctic environment and the complexity of ingestion-influencing parameters. However, several authors mentioned fishing equipment as a potential source of the plastics ingested (Nielsen et al., 2014; Liboiron et al., 2019; Saturno et al., 2020), which is expected since some parts of the Arctic Ocean are productive areas with high fishing activities all year round (Grøsvik et al., 2018).

The results vary among species from the same region, indicating that, indeed, plastic ingestion is species-specific (Lopes et al., 2020). The exposure might be of less importance than once thought. Many parameters are assumed to be involved in plastic ingestion by fish (Horton et al., 2018; Collard et al., 2019) and ecology and morphology are also playing a role (Lusher et al., 2016; Collard et al., 2017; Peters et al., 2017).

4. Seabirds

Plastic ingestion in Arctic seabirds has recently been reviewed by Baak et al. (2020a). Their objectives were to fill knowledge gaps and focus on species suitable for monitoring plastic pollution in the Arctic. Therefore, to avoid a significant overlap with Baak et al. (2020a), we focused on studies whose principal objective was the investigation of plastic ingestion in Arctic seabirds and no attempt will be made to critically review their sampling design, extraction protocol or identification techniques. We gently advise readers to read other reviews if they look for a constructive and complete overview turned to monitoring perspectives, plastic pollution policies in relation to seabirds, and to methods including grey literature and opportunistic studies on plastic occurrence in Arctic seabirds (Provencher et al. 2019a & b; Baak et al., 2020a; Linnebjerg et al., 2021).

As shown in Fig. 3 and Table 2, the Procellariiformes were the most studied group, almost exclusively represented by the northern fulmar (*Fulmarus glacialis*, hereafter called "fulmar") with data reported in 16 different publications. The Alcidae family is also well represented with 10 studies. Among the publications we reviewed, Day (1985) and Robards et al. (1995) were the most complete as they included several species, but not always with a sufficient sampling number for each species (Table S1). Unsurprisingly, the fulmar was the species with the highest frequency of plastic occurrence in the stomach regardless of the sampling date. Studies from the 1980s already showed a frequency of occurrence (FO) ranging between 40% to 80% depending on the area investigated (van Franeker, 1985; Day, 1985). Similarly, the most recent studies also reported high FOs compared to other species examined from the same sampling region (Poon et al., 2017; Baak et al., 2020b; Bourdages et al., 2021). Those findings support the idea that the fulmar is a key indicator of marine plastic pollution in the Arctic region (Baak et al., 2020a).

Table 1
Frequencies of occurrence of ingested plastic in Arctic fish (as in Fig. 2). FO: frequency of plastic occurrence.

Species	Order	Sampling location	FO	Study
Somniosus microcephalus	Squaliformes	Northwestern Svalbard	3%	Leclerc et al., 2012
Somniosus microcephalus	Squaliformes	Greenland coast	8.3%	Nielsen et al., 2014
Gadus morhua	Gadiformes	Norwegian coast	0%	Bråte et al., 2016*,**
Gadus morhua	Gadiformes	Newfoundland & Labrador, Canada	2.4%	Liboiron et al., 2016
Boreogadus saida	Gadiformes	NW Svalbard & Eurasian basin	2.8%	Kühn et al., 2018
Boreogadus saida	Gadiformes	Greenland Sea	18%	Morgana et al., 2018
Triglops nybelini	Scorpaeniformes		34%	
Gadus morhua	Gadiformes	Newfoundland & Labrador, Canada	1.7%	Liboiron et al., 2019
Mallotus villosus	Osmeriformes		0%	
Salmo salar	Salmoniformes		0%	
Gadus morhua	Gadiformes	Newfoundland & Labrador, Canada	1.4%	Saturno et al., 2020
Gadus ogac	Gadiformes	Greenland coast	100%	Granberg et al., 2020

* Only results from the Arctic region are included here.

** Values recovered from a bar graph, might not be accurate.

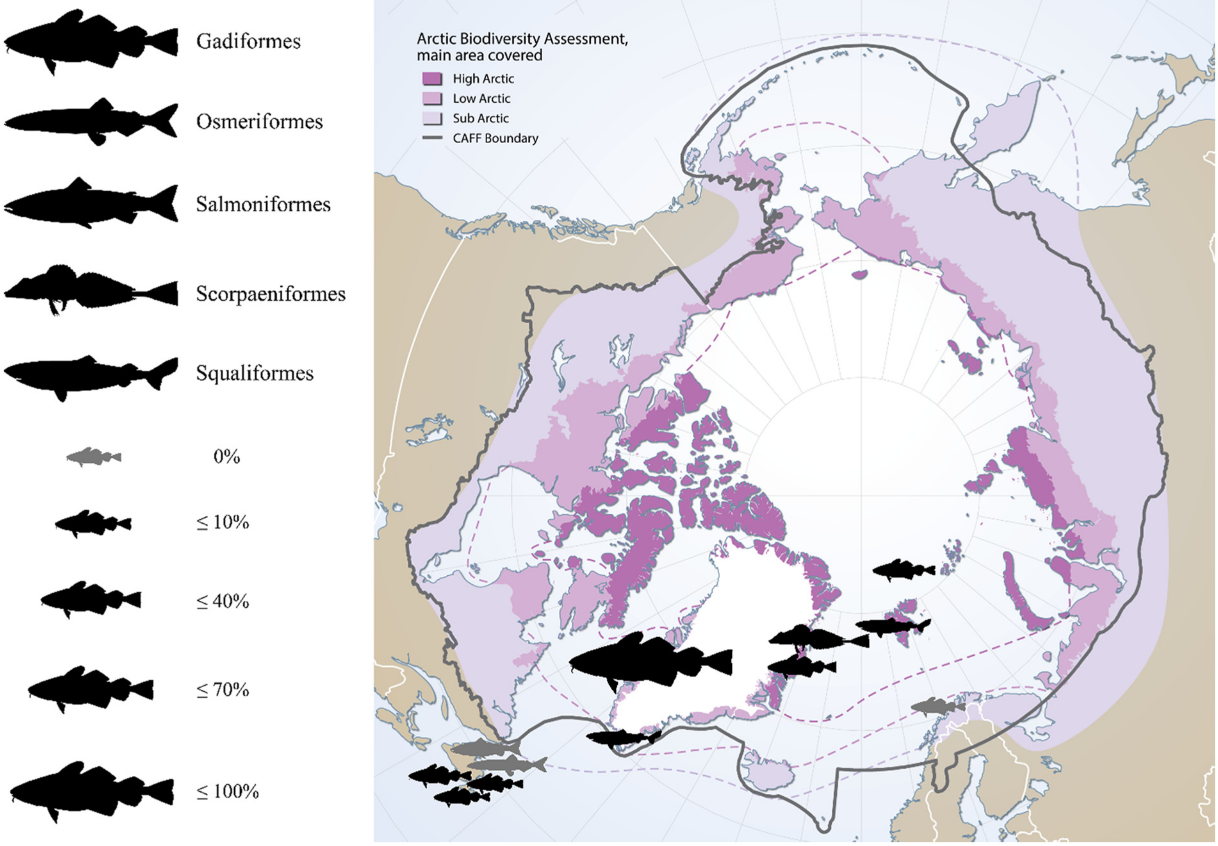

Fig. 2. Map showing the sampling locations of fish investigated for plastic ingestion, categorised by order and by associated frequency of plastic occurrence (FO). The symbol's size reflects the percentage of FO. If a species has been sampled at several places within the same study, only one symbol is shown on the map. Modified from Culp et al. (2012).

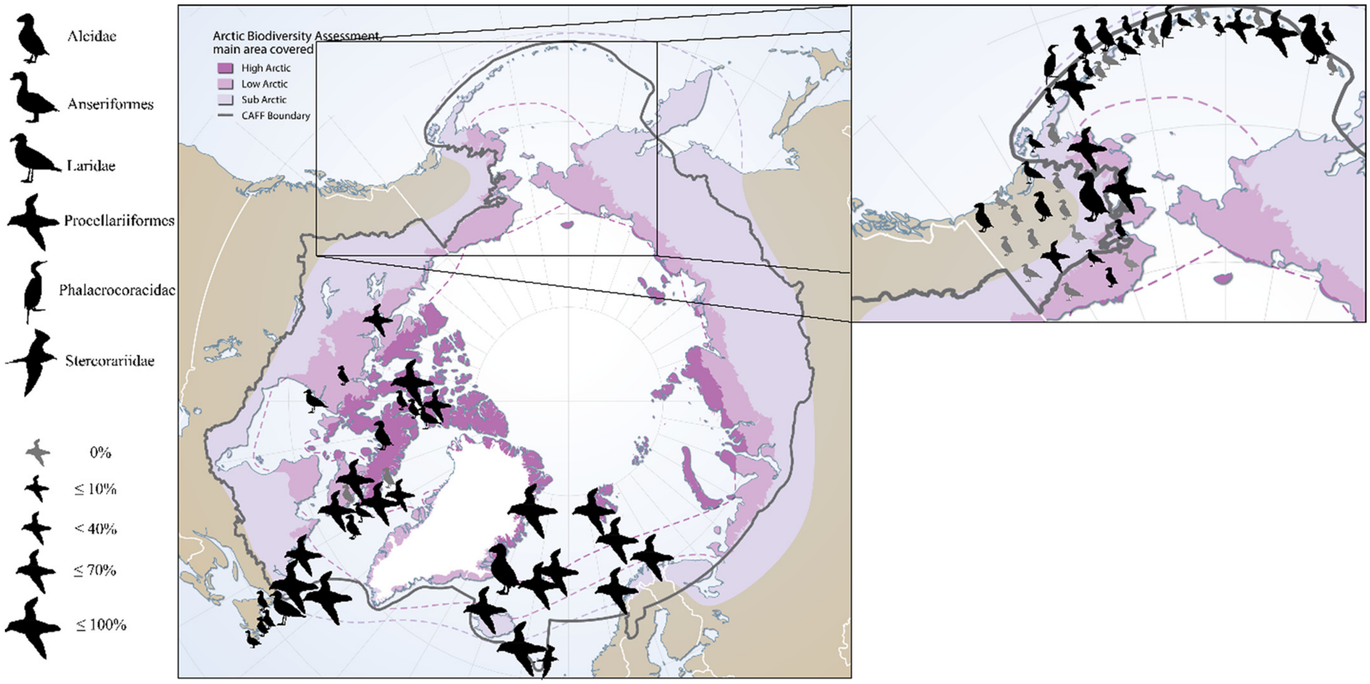

Fig. 3. Map showing the sampling locations of seabirds investigated for plastic ingestion, categorised by group and by associated frequency of plastic occurrence (FO). The symbol's size reflects the percentage of FO. Only studies focusing on plastic ingestion are included and species represented by less than 10 individuals for a given sampling site are not shown. Data from Alaska and Canadian Arctic (Day, 1985) are randomly placed inside the continental Alaska state and northern continental Canada, respectively. Data from Alaska (Robards et al., 1995; Padula et al., 2020) are randomly placed along the Aleutian Islands. If a species has been sampled at several places within the same study, only one symbol is shown on the map. Modified from Culp et al. (2012).

Table 2
Frequencies of occurrence of ingested plastic in Arctic seabirds (as in Fig. 3). FO: frequency of plastic occurrence. Only data from a sampling set with ten or more individuals are reported in both this table and Fig. 3. Studies not reporting data in frequency of occurrence are not included in this table.

Species	Family/order	Sampling location	FO	Study
Fulmarus glacialis	Procellariiformes	Bear Island	~80%	van Franeker, 1985
		Jan Mayen	~80%	
Fulmarus glacialis	Procellariiformes	Alaska	58%	Reviewed in Day, 1985
Fulmarus glacialis	Procellariiformes	Canadian Arctic	40%	
Fulmarus glacialis	Procellariiformes	Jan Mayen Island	76%	
Ardenna grisea	Procellariiformes	Alaska	43%	
Ardenna tenuirostris	Procellariiformes	Alaska	84%	
Clangula hyemalis	Anseriformes	Alaska	0%	
Melanitta perspicillata	Anseriformes	Alaska	0%	
Bucephala islandica	Anseriformes	Alaska	0%	
Larus glaucescens	Laridae	Alaska	0%	
Larus hyperboreus	Laridae	Alaska	3%	
Rissa tridactyla	Laridae	Alaska	5%	
Rissa tridactyla	Laridae	Canadian Arctic	12%	
Rissa brevirostris	Laridae	Alaska	13%	
Sterna paradisaea	Laridae	Alaska	0%	
Uria aalge	Alcidae	Alaska	0%	
Uria lomvia	Alcidae	Alaska	1%	
Uria lomvia	Alcidae	Canadian Arctic	1%	
Cepphus columba	Alcidae	Alaska	0%	
Brachyramphus marmoratus	Alcidae	Alaska	0%	
Synthliboramphus antiquus	Alcidae	Alaska	0%	
Aethia psittacula	Alcidae	Alaska	75%	
Aethia pusilla	Alcidae	Alaska	1%	
Aethia cristatella	Alcidae	Alaska	0%	
Cerorhinca monocerata	Alcidae	Alaska	0%	
Fratercula cirrhata	Alcidae	Alaska	15%	
Fratercula corniculata	Alcidae	Alaska	37%	
Fulmarus glacialis	Procellariiformes	Alaska	84.5%	Robards et al., 1995
Oceanodroma leucorhoa	Procellariiformes		48%	
Oceanodroma furcata	Procellariiformes		86%	
Phalacrocorax urile	Phalacrocoracidae		0%	
Larus glaucescens	Laridae		0%	
Rissa tridactyla	Laridae		8%	
Rissa brevirostris	Laridae		27%	
Uria aalge	Alcidae		1%	
Uria lomvia	Alcidae		0%	
Ptychoramphus aleuticus	Alcidae		11%	
Aethia psittacula	Alcidae		94%	
Aethia pusilla	Alcidae		0%	
Aethia pygmaea	Alcidae		0%	
Aethia cristatella	Alcidae		2.5%	
Brachyramphus marmoratus	Alcidae		0%	
Brachyramphus brevirostris	Alcidae		0%	
Synthliboramphus antiquus	Alcidae		0%	
Cepphus columba	Alcidae		3%	
Fratercula cirrhata	Alcidae		25%	
Fratercula corniculata	Alcidae		37%	
Fulmarus glacialis	Procellariiformes	Davis Strait, Canada	36%	Mallory et al., 2006
Fulmarus glacialis	Procellariiformes	Devon Island, Canada	31%	Mallory, 2008
Fulmarus glacialis	Procellariiformes	Nunavut, Canada	84%	Provencher et al., 2009
Uria lomvia	Alcidae	Nunavut, Canada	11%	Provencher et al., 2010
Fulmarus glacialis	Procellariiformes	Westfjords, Iceland	79%	Kühn and van Franeker, 2012
Uria aalge	Alcidae	Newfoundland, Canada	7%	Bond et al., 2013
Uria lomvia	Alcidae			
Somateria mollissima	Anseriformes	Newfoundland, Canada	2%	English et al., 2015
Alle alle	Alcidae	Newfoundland, Canada	14%	Fife et al., 2015
Fulmarus glacialis	Procellariiformes	Isfjord, Svalbard	87.5%	Trevail et al., 2015
Alle alle	Alcidae	Kap Höegh, East Greenland	100%	Amélineau et al., 2016
Stercorarius skua	Stercorariidae	Skúvoy, Faroe Islands	30%	Hammer et al., 2016
Fulmarus glacialis	Procellariiformes	Norway	81%	Herzke et al., 2016
Fulmarus glacialis	Procellariiformes	Prince Leopold Island, Canada	89%	Poon et al., 2017
Rissa tridactyla	Laridae		9%	
Uria lomvia	Alcidae		0	
Cepphus grylle	Alcidae		0	
Fulmarus glacialis	Procellariiformes	Southern Labrador Sea, Canada	79%	Avery-Gomm et al., 2018
Fulmarus glacialis	Procellariiformes	Labrador Sea	97%	Provencher et al., 2018
Larus smithsonianus	Laridae	Newfoundland, Canada	61%	Seif et al., 2018
Fulmarus glacialis	Procellariiformes	Northeast Greenland	90%	Ask et al., 2020
		Faroe Islands	87%	
Fulmarus glacialis	Procellariiformes	Eastern Baffin Island, Canada	72%	Baak et al., 2020b
Rissa tridactyla	Laridae		15%	

Table 2 (*continued*)

Species	Family/order	Sampling location	FO	Study
Uria lomvia	Alcidae		0	
Cepphus grylle	Alcidae		0	
Phalacrocorax pelagicus	Phalacrocoracidae		30%	
Phalacrocorax urile	Phalacrocoracidae	Alaska	30%	Padula et al., 2020
Fratercula cirrhata	Alcidae		37%	
Fulmarus glacialis	Procellariiformes	Labrador strait	90%	Provencher et al., 2020
Fulmarus glacialis	Procellariiformes	Nunavut, Canada	74%	Bourdages et al., 2021
Uria lomvia	Alcidae		17%	

In addition to the Procellariiformes, the Alcidae family (auks) has been studied quite often but almost only in North America (e.g. Day, 1985; Bond et al., 2013; Poon et al., 2017). The average occurrence of plastics in those birds was much lower than in fulmars, with only three studies reporting frequencies of occurrence above 50% (Day, 1985; Robards et al., 1995; Amélineau et al., 2016). Altogether, in those studies, two Alcidae species exceeded that percentage out of 14 species investigated (*Aethia psittacula* and *Alle alle*).

Among the less studied families, the Laridae (gulls) and the Stercorariidae (skuas) showed in some cases quite high levels of ingestion (FOs of 61% and 30%, respectively) (Hammer et al., 2016; Seif et al., 2018). However, given the low number of publications about those bird families, no conclusion can be proposed and further investigations are needed to confirm those data.

Most data about plastic ingestion by seabirds come from Canada. There is work in progress in the European Arctic and some papers are available from previous years (Trevail et al., 2015; Amélineau et al., 2016; Kühn et al., 2021; Neumann et al., 2021), but data are clearly lacking from the European and Russian regions. In the European Arctic, results mostly relate to the fulmar although studies in Greenland and in Canada showed that other species could be at risk and are worth investigating.

5. Marine mammals

5.1. Cetaceans

Most information on plastic ingestion by marine mammals in the Arctic is for cetaceans. As far as we are aware, only one study looked specifically at plastic ingestion: Moore et al. (2020) investigated MPs in the gastrointestinal tract of seven beluga whales (*Delphinapterus leucas*) caught in 2017–2018 in Tuktoyaktuk, Northwest Territories, Canada. All seven whales contained MPs, averaging 97 ± 42 MPs per individual. Fibres constituted 49% of the MPs.

Most of the other reports of plastic ingestion by cetaceans are found in papers describing the diet of those organisms. Several species have been reported to have ingested plastics (Table S1): three studies report plastic ingestion by sperm whales (*Physeter macrocephalus*) and fin whales (*Balaenoptera physalus*). Martin and Clarke (1986) examined stomach contents of 221 sperm whales caught between 1977 and 1981 between Iceland and Greenland and found that an unspecified number of whales had ingested plastics, in addition to other non-food items such as rocks and wood. Of particular note is that one sperm whale had ingested a discarded fishing net weighing 63 kg which was stuck between two stomach compartments. Similarly, Lambertsen and Kohn (1987) found a 3-gallon plastic bucket in the intestine of a sperm whale caught in Iceland. Of the 82 fin whales caught in the 1985 whaling season in Iceland, six had ingested plastics (Sadove and Morreale, 1989). The bowhead whale (*Balaena mysticetus*) has also been shown to ingest plastics (Lowry, 1993; Finley, 2001), but the literature does not give much details about it. Walker and Hanson (1999) reported plastic ingestion by two Stejneger's beaked whales (*Mesoplodon stejnegeri*) stranded in 1988 and 1994 on Adak Island, Alaska, USA. They had ingested plastic twine 4–7 mm in diameter and up to 2 m long.

Finally, in 2016 a narwhal (*Monodon monoceros*) stranded in Belgium. Upon necropsy, it was discovered that the narwhal had ingested large amounts of plastics (Haelters et al., 2018). The authors conclude that the plastics were in all likelihood ingested close to death and thus does not reflect foraging in the Arctic. Despite this narwhal stranding in Belgium, it is an Arctic species and closely associated with sea ice (Laidre and Heide-Jørgensen, 2011) and included in this review as it shows that narwhals can ingest plastics.

5.2. Pinnipeds

Altogether, six seal species have been investigated for plastic ingestion in the Arctic, two of which had ingested plastics (Donohue et al., 2019; Bourdages et al., 2020; Pinzone et al., 2021). Scats from northern fur seals (*Callorhinus ursinus*) collected in 2015 from colonies on St. Paul Island ($n = 18$) and Bogoslof Island ($n = 17$), Alaska, USA (as well as one in California, USA which is not included here) were examined for plastics (Donohue et al., 2019). It is assumed that each scat comes from a unique individual. Both fragments and fibres were found in scats. At St. Paul Island ten out of the 18 scats contained fragments, with a mean number of 28.0 ± 26.4 fragments/positive sample. Ten out of the 17 collected scat samples from Bogoslof Island contained fragments, but the mean number of fragments was lower (9.3 ± 7.4 fragments/positive sample). None of the substrate samples or controls contained any fragments. For fibres, however, contamination of substrate and control samples was an issue. Fibres were found in 50%, 41%, 47% and 74% of scats from St. Paul Island, Bogoslof Island, blank samples and filter-air samples. This illustrates the pervasive issue of MP contamination (Hidalgo-Ruz et al., 2012; Hermsen et al., 2018; Scopetani et al., 2020).

Pinzone et al. (2021) examined the gastrointestinal tract of hooded seal (*Cystophora cristata*, $n = 8$) and harp seal (*Pagophilus groenlandicus*, $n = 10$) pups caught in the Greenland Sea in 2017. One hooded seal pup had ingested two pieces of plastic derived from a food package. None of the harp seals had ingested plastics.

Bourdages et al. (2020) did not find any plastic (>425 μm) in stomachs from ringed seals (*Pusa hispida*, $n = 135$), bearded seals (*Erignathus barbatus*, $n = 6$) or harbour seals (*Phoca vitulina*, $n = 1$) caught in Nunavut, Canada, between 2007 and 2019.

5.3. Polar bears

Thirteen out of 51 examined polar bears (*Ursus maritimus*) from Alaska (1996–2018) had ingested plastics (Stimmelmayr et al., 2019). Most of the plastics were identified as plastic bags from local shops as well as black garbage bags. Other plastic pieces of unknown origins were also found in the stomachs. The sizes ranged from a few centimetres up to complete bags. In two cases the pyloric outlet was probably obstructed with non-food items. Additionally, observations were made before subsistence harvesting of two aggressive polar bears, which had ingested large amounts of plastics, which may be linked to pyloric outlet obstructions. In 1968 and 1969, Russell (1975) collected polar bear scats in the James and Hudson Bay areas of the Canadian Arctic. For scats collected on islands, 2% contained debris classified as “other”, while 9% of scats collected on the mainland contained “other” debris (the debris category also includes sand and woodchips, which have purposely been excluded in this review—as such the numbers here differs from Table 2 in Gormezano and Rockwell (2013). Russell (1975) also notes that six scats contained pieces of styrofoam. Gormezano and Rockwell (2013) analysed 642 polar bear scats collected in western Hudson Bay from 2006 to 2008. They found garbage (defined as any item of anthropogenic origin, e.g. plastics, foam rubber, and duct tape, but also apple peel, cantaloupe seeds, and glass) in 6.4% of the scats (41 out of 642). Between 2003 and 2010, 119 scats were collected around the Svalbard archipelago (Iversen et al., 2013). Of the 119 scats, three (2.5%) contained plastics. Furthermore, a polar bear in the Hinlopen Strait, Svalbard, was documented with a piece of plastic film in its mouth (Bergmann et al., 2017, see Fig. 2), suggesting that polar bears might be ingesting plastics even in areas far away from human settlements and associated landfills.

This section highlights a lack of plastic pollution studies with corresponding adapted protocols. Although we know that marine mammals may ingest plastics, data are insufficient to establish baselines, understand the extent of plastic ingestion and its impacts. In some regions, marine mammals are hard to sample for many reasons but an international sampling effort turned towards stranded organisms, mainly cetaceans, could help gathering data and, at least, assess how hazardous, if not lethal, plastic pollution is towards those sentinel species.

6. Terrestrial mammals

Although entanglements have been reported for a couple of species such as the Svalbard reindeer (*Rangifer tarandus platyrhynchus*) (e.g. Nashoug, 2017) and the Grant's caribou (*Rangifer tarandus granti*) (e.g. Beach et al., 1976), to the best of our knowledge, there is no available information on plastic ingestion by Arctic terrestrial mammals, other than the arctic fox (*Vulpes lagopus*) and the arctic wolf (*Canis lupus arctos*). For the arctic fox, only one study was done specifically to assess potential plastic ingestion, whereas we found five diet studies which also include information on ingestion of human litter (with varying definitions of “human litter”). We were able to find only one diet study on the arctic wolf (Marquart-Petersen, 1998) reporting ingestion of plastic and other garbage.

Stomachs and intestines of arctic foxes ($n = 20$) caught in Svalbard in 2017–2018 as part of the annual trapping were examined for plastics and other anthropogenic litter (Hallanger et al., pers. comm.). Parts of a cream carton were found in one fox and cotton rope in another. An earlier study on the diet of arctic foxes in Svalbard found garbage (defined as plastic and paper) in 5% of examined foxes ($n = 751$, 1977–1989), but further details are not given (Prestrud, 1992). Similarly, 6% of arctic fox scats ($n = 566$) from Prudhoe Bay, Alaska, contained garbage (defined as any manmade substance commonly associated with food, e.g. plastic wrap and aluminium foil) in 1975–1978 (Garrott et al., 1983). In contrast, West (1987) found no human litter in arctic fox scats ($n = 193$) collected from the Aleutian Islands, Alaska, between 1981 and 1982. However, stomach analysis of arctic foxes from the same region showed that 9% (8 out of 86, collected in summer 1975) of the examined foxes had ingested human litter (defined as wood, plastic or rubber) (West, 1987). In a third study from Alaska, Anthony et al. (2000) examined 619 gastrointestinal tracts of arctic foxes from the Yukon-Kuskokwim Delta between 1986 and 1991. The FO of gastrointestinal tracts containing human refuse (the article does not define the term) ranged from 0% in 1988 to 4% in 1986 and 1989 (for FOs from all six years, the reader is kindly referred to Table 1 in Anthony et al., 2000). In a study of gastrointestinal tracts from arctic foxes caught in different areas of Greenland in 1992–1993 ($n = 254$), Kapel (1999) found a greater FO of human litter (defined as plastics, paper, clothes, and rope) in foxes caught close to human settlements. For example, the FO of human litter in arctic foxes caught at the Kangerlussuaq air base was 26% compared to 0% in foxes from the surrounding areas. Overall the FO of ingestion of human litter varied between sites and ranged from 0% to 50% (Thule air base).

The arctic wolf has been reported to have ingested plastic and other garbage in Greenland (Marquart-Petersen, 1998). The author analysed 451 samples of wolf faeces from north and east Greenland in the 1990s. Three of those samples contained plastic, i.e. nylon rope, remains of a plastic bag and an unknown plastic piece.

7. Perspectives and knowledge gaps

Although it has been recommended to avoid descriptive studies in the field of plastic pollution to focus more on the long-term impacts (Collard et al., 2019), setting baselines on the short-term in the Arctic is of high relevance. Too few areas have been sampled so far (Fig. 1) regardless of the organism studied. In this case, studying environmental plastic levels would help to target relevant areas and species at risk for monitoring and/or ecotoxicological studies under controlled conditions.

As illustrated by Fig. 1, plastic levels in several areas of the Arctic are yet to be investigated. Especially, plastic contamination levels in biota are almost totally unknown in the Russian Arctic or at least, not easily available for the international scientific community. Beside the huge area the Russian Arctic represents, it comprises the three largest Arctic rivers: the Ob, Yenisei and Lena rivers (Slaymaker, 2020) which are also among the 10 largest rivers on Earth in terms of basin magnitude (Peterson, 2002; Milliman and Farnsworth, 2011). A model described by Lima et al. (2021) predicted high densities in point zones of the Arctic Ocean, including several seas bordering Russia (Chukchi, Bering, Kara and Laptev Seas). It can be explained by the flowing of North Pacific and North Atlantic currents into the Arctic (Lima et al., 2021) but also from more local inputs. The Arctic Ocean receives around 11% of global river discharge while it is the smallest ocean (Lammers et al., 2001; Slaymaker, 2020), making it the most river-influenced ocean on the planet (Vörösmarty et al., 2000). Furthermore, rivers are known to be the main—or one of the main—plastic sources to coastal areas (Andrady, 2011; Lima et al., 2014; Lebreton et al., 2017). Given this, the Arctic Ocean could be dramatically exposed to plastic litter, especially the Russian Arctic, with almost unknown consequences on biota. It is therefore of high priority to investigate plastic levels in both abiotic and biotic compartment to identify potential hotspot zones.

Van Sebille et al. (2012) and Cózar et al. (2017) have shown evidence through modelling that the Barents Sea is becoming a sink for plastic debris and might become another garbage patch, i.e. a gyre trapping marine debris, in addition to those already existing in the five major oceans. However, only three studies have performed a fauna sampling in that sea, one being at the limit of the Barents and the Greenland Seas (van Franeker, 1985; Herzke et al., 2016; Knutsen et al., 2020). Further research in the Barents Sea, in all compartments, should be conducted in order to verify the model predictions, to further identify exposed species and select suitable ones for biomonitoring purposes.

Biomonitoring of plastic pollution is awaited by scientists as well as international working groups such as the Arctic Monitoring and Assessment Programme (AMAP), the Protection of the Arctic Marine Environment (PAME), the International Arctic Science Committee (IASC) and the United Nations Environment Programme (UNEP). These expert groups pay a particular attention to plastic pollution. Surprisingly, as far as we know, the fulmar is the only acknowledged bioindicator for this type of pollution (OSPAR, 2021). Establishing a monitoring programme in the Arctic would help the scientific community to (1) establish spatial and temporal trends, (2) evaluate the consequences of human action in the Arctic, and finally (3) inform policy makers (Derocles et al., 2018). There is no biomonitoring programme of plastic pollution in the Arctic. The northern fulmar is probably the most studied species in northern latitudes because it has been defined as a biomonitoring species in the North Atlantic and is found in the Arctic. However, there is no clear programme for sampling and analyses of fulmars in the Arctic. The OSPAR Commission has defined common guidelines for the use of fulmars as bioindicators of plastic pollution to assess changes in the North Atlantic (OSPAR, 2010). Scientists are now gathering data, experience and methods of great value concerning fulmars to move forward with this (Trevail et al., 2015; Provencher et al., 2018; Baak et al., 2020a). OSPAR also defined goals representing the maximal limit of contamination to be reached on a long-term basis (OSPAR, 2008; van Franeker et al., 2011). One step further should be taken to launch a biomonitoring programme in the Arctic through the northern fulmar as a bioindicator. Although it has been studied in seven different Arctic countries, several temporal and spatial gaps do remain (Baak et al., 2020a). In addition to a bird species, a fish species should also be used for biomonitoring (ICES, 2015). Fish are exclusively linked to water and will provide an overview of plastic pollution in the water column, and not only on floating particles as the fulmar does. Although few data exist on plastic ingestion by Arctic fish, the polar cod could be the most suitable candidate. Among Arctic fish species, it is one of the most common fish in the Arctic and has a circumpolar distribution unlike, for example, the Atlantic cod. It is also sensitive to this type of pollution (Kühn et al., 2018) and is often found close to the sea ice which is a source of MPs (Obbard et al., 2014; Peeken et al., 2018) making this species particularly exposed, and perhaps, threatened. Furthermore, the polar cod is an indicator species for other pollutants (Nahrgang et al., 2010), a key species in the Arctic ecosystem and a prey for marine mammals, seabirds and predator fish (Hop and Gjøsæter, 2013). Beside its ecological relevance, the polar cod fulfils many recommended criteria to select a species for biomonitoring (Collard et al., 2019; GESAMP, 2019) most likely making it the best candidate among Arctic fish species.

As already mentioned above, the fulmar has been reported to ingest more plastic pieces than other birds (Table 2). In fulmars, plastic pieces are usually found in the proventriculus and the gizzard, the proportion varying along the breeding season (Mallory, 2008). At the end of the summer, most plastic pieces are in the gizzard where they may be broken down into smaller pieces to be further evacuated. Hard pieces, including plastics, are ground up in the gizzard until they are small enough to pass into the intestine (van Franeker and Law, 2015). A positive correlation between the number of pieces in the gut and in the guano has been reported (Provencher et al., 2018), potentially showing that plastic pieces eventually reach the intestine and be evacuated in the guano. Some studies reported high numbers of plastic pieces, e.g. 200 pieces in a single individual (Trevail et al., 2015), and therefore impacts might be expected. Indeed, many of the studies, including the one by Trevail et al. (2015), provided data for plastics of 1 mm or larger (e.g. Avery-Gomm et al., 2018; Kühn and van Franeker, 2012; Herzke et al., 2016; Poon et al., 2017). Although small, when dozens of such plastic pieces are trapped in the gizzard (roughly a few cubic centimetres when full), it might be expected that the journey of natural prey through the stomachs is impaired in the gizzard but, to the best of our knowledge, this has not yet been studied in wild seabirds. Mechanical impacts can be expected and perhaps, toxicological impacts too. Plastic particles carry pollutants (reviewed in Verla et al., 2019) and are believed to be leached out within the organism once ingested (reviewed in Wang et al., 2018, e.g. Neumann et al., 2021). Both mechanical and toxicological impacts need to be further investigated, especially in species known for ingesting high quantities of plastic pieces, such as the fulmar. More globally, seabirds can also be a transport medium of plastics from sea to land as highlighted in recent studies (Bourdages et al., 2021; Hamilton et al., 2021). Bourdages et al. (2021) calculated that millions of microplastics could be deposited on land around the seabird colonies each year. That finding opens a new field of plastic pollution research about its dynamics and the impacts such transport has on terrestrial ecosystems.

To perform comparable monitoring studies, methods should be similar. One of the major issues in the plastic pollution research is the lack of standardization (Hermsen et al., 2018; Collard et al., 2019; Gatidou et al., 2019; Prata et al., 2019; Provencher et al., 2019b), regardless of the species, matrix or region of the world. Discrepancies occur in all steps, from sampling to expression of results. Recommendations on the different steps occurring in plastic research on biota have already been made in previous reviews (Provencher et al., 2017; Hermsen et al., 2018; Collard et al., 2019; Markic et al., 2019; Prata et al., 2019). It should be noted that Hermsen et al. (2018) proposed a quality assessment method, based on an ICES protocol (ICES, 2015), which can be used for all studies aiming at detecting plastic in marine biota. The score obtained through that system will inform about the reproducibility and reliability of the method described. That system concerns only global criteria such as the occurrence of negative controls or polymer identification, but it is suggested as an interesting first step towards standardization. A second step would be to harmonize both the digestive agent, when digestion of stomach contents is done, and the lower size limit of extracted particles. We suggest using KOH as the main digestive agent whatever organism is investigated. So far, it is one of the most common chemicals used to degrade biological matter and it is non-destructive for plastic materials, other artificial polymers (Dehaut et al., 2016; Karami et al., 2017; Kühn et al., 2017; Zhang et al., 2017; Markic et al., 2019), and both natural and artificial fibres (Treilles et al., 2020) unlike other agents such as acids (Dehaut et al., 2016). Some authors heated the mixture at different temperatures (Rochman et al., 2015; Jamieson et al., 2019; Thiele et al., 2019) but heating is not recommended to ensure full recovery of plastic materials (Munno et al., 2018; Treilles et al., 2020). Regarding the lower size limit of particles extracted, we suggest going down to 20 μm, as first proposed by the Marine Strategy Framework Directive (Galgani et al., 2013). Small MPs (<1 mm, Imhof et al., 2012, Vianello et al., 2013) quantities are expected to increase drastically due to the fragmentation of macro- and large microplastics in the environment (Cózar et al., 2014). Those MPs should be the focus in further research as they can be ingested by a wider range of organisms (Cózar et al., 2014) and were found to impact organisms more severely, for example, by transfer through the intestinal wall towards other tissues (Vandermeersch et al., 2015; Lu et al., 2016; Franzellitti et al., 2019).

Beside sea ice, the Arctic is also known for its numerous glaciers. As of 2021, to the best of our knowledge, no Arctic glacier has been studied in the frame of plastic pollution despite their strong link to organisms. Indeed, glacier fronts are a privileged foraging place for many seabirds and marine mammals (Lydersen et al., 2014). At present, only one study investigated plastic levels in a glacier, and more precisely in the cryoconite (Ambrosini et al., 2019). That study processed samples from an Italian alpine glacier and reported for the first time microplastic debris. Atmospheric transport is thought to be one of the main contributors because fibres represented the majority of the microplastics. The cryoconite is also enriched in other anthropogenic elements such as heavy metals (Baccolo et al., 2017) that might be adsorbed onto plastic already present in cryoconites. Glacier fronts can potentially be a bigger threat for Arctic organisms as they may be a source of pollutants and plastics separately but also of plastics with sorbed contaminants.

In 2016, the fibre production surpassed 100 million metric tons in a single year (The Fibre Year, 2017). Geyer et al. (2017) have estimated that, between 1950 and 2015, around 600 million metric tons of artificial fibres (polyester, polyamide and acrylic polymers) were discarded in the environment where they are accumulating. Unsurprisingly, fibres are then the most common microplastic shape found worldwide in many matrices (Dris et al., 2016; Carr, 2017; Salvador Cesa et al., 2017; Bessa et al., 2018; Collard et al., 2019; Wang et al., 2019). In the Arctic, fibres are pervasive (Ross et al., 2021) and were reported by several studies as the major shape of plastic in both abiotic (Obbard et al., 2014; Lusher et al., 2015; Mu et al., 2019a, 2019b; von Friesen et al., 2020) and biotic compartments (Bråte et al., 2018; Fang et al., 2018; Liboiron et al., 2019). According to the literature reviewed here, fibres dominate plastic contamination in smaller organisms. Most of the plastic fibres (polyethylene terephthalate, polyamide, acrylic) are heavier than seawater and sink once at sea. For example, fulmars were the most investigated group. Fulmars feed on small organisms at the sea surface where plastic fibres are just in transit between their source and their sink, which make them briefly available for most seabirds. Although fibres are not expected to be found in megafauna digestive tract, they sometimes occur in relatively high quantities. In the case of beluga whales, 49% of MPs found in beluga whales were fibres (Moore et al., 2020), whereas one would have expected fragments to dominate. Those fibres were too small to be deliberately ingested by those whales and therefore, a trophic transfer from prey is suspected (Moore et al., 2020). Even though marine megafauna might be less exposed to fibres, they still do ingest some, highlighting the ubiquity of fibres in biota.

Future research should also focus on fibres, e.g. their levels in biota but also how they impact the organisms. To a greater extent, other anthropogenic fibres can be retrieved from biota samples through extraction protocols targeting plastic particles. Thus, we encourage researchers to include all fibres handled by humans in their reports and publications as they might represent another hazardous type of particles to organisms (Remy et al., 2015; Collard et al., 2019; Collard et al., 2021). Moreover, fibres could be the most consumed particles by humans when common food and beverages, e.g. bottled and tap water, beer, salt, are taken into consideration (Cox et al., 2019). Furthermore, contamination of samples by fibres is also a pervasive issue (e.g. Sundet et al., 2016, 2017, Donohue et al., 2019) and future studies should include appropriate blanks, e.g. procedural and field blanks, to account for this.

The research on plastic pollution in Arctic terrestrial mammals, birds, and invertebrates, as well as in Arctic abiotic terrestrial compartments in general, is still in its infancy. As in other regions, research efforts have mainly focused on marine or aquatic pollution (Rillig, 2012; Wang et al., 2020). Among the older studies cited in this review (Section 6), none clearly defined and characterised the ingested litter. Terrestrial organisms in other regions have been shown to ingest plastics, sometimes at high levels (Zhao et al., 2016), and may be affected by that pollution (reviewed in de Souza Machado et al., 2018). Corvids, for example, might be affected by plastic ingestion given their feeding strategy. Although entanglements of Arctic terrestrial fauna in macroplastics have been frequently observed and/or reported (Nashoug, 2017; Hallanger and Gabrielsen, 2018; Singh et al., 2021), ingestion reports are much scarcer. Collaborations with Indigenous Peoples and local hunters would relatively easily give scientists access to such data. Many terrestrial animals are hunted across the Arctic such as moose (*Alces alces*), muskox (*Ovibos moschatus*), and several species of deer (Cervidae), geese (genera *Anser* and *Branta*), and ptarmigans (*Lagopus* spp.). Those hunted animals could also serve scientific purposes in addition to recreation and/or subsistence hunting. The digestive tract is not usually of interest for local hunters but it is for plastic pollution research. Some studies, especially in Canada, already showed such successful collaborations although mostly for marine animals (e.g. Bond et al., 2013, Bourdages et al., 2020, Moore et al., 2020, Hallanger et al., pers. comm.). We suggest that future studies involve more terrestrial matrices, including biota. In the latter case, collections of organs from hunted animals would reduce the impact of sampling on the animals' populations. This would constitute a new facet of plastic pollution in the Arctic that would help in understanding this global threat.

The occurrence of plastic debris in the Arctic has also another hidden impact: the dispersal of Arctic species and the introduction of new ones. To our knowledge, only one study reported the presence of both common invertebrates in Svalbard (*Electra* spp., *Eucratea loricata*, *Semibalanus balanoides*) and other species from further south on beached macroplastics (Weslawski and Kotwicki, 2018). They reported *Lepas anatifera*, the pelagic gooseneck barnacle, which has never been reported in Svalbard before. They also suspected that plastic drifting from warmer waters to Svalbard has led to the reappearance of the genus *Mytilus* on Svalbard, as well as favourable conditions such as the heating of coastal Svalbard waters. Similarly, plastics could be vectors of pollutants to the Arctic. A plastic flux between 62,000 and 105,000 tons has been estimated to reach the Arctic each year if the maximum volume transport of ocean water (Zarfl and Matthies, 2010), bringing along pollutants in huge quantities. Zarfl and Matthies (2010) have estimated that the annual PCB, PBDE and PFOA fluxes to the Arctic through plastic debris ranged from 250 g to 130 kg, from 25 g to 5.9 kg, and reached 4.6 kg at maximum, respectively.

Many processes will lead to an increase of plastic levels in the Arctic and consequently, to an increase of this threat for Arctic species: a decrease in sea ice volume, melting of glaciers, an increase in maritime activities, development of tourism (Grøsvik et al., 2018), a continuous release through wastewater outlets, a slower degradation rate of plastic material in cold environments (Bergmann and Klages, 2012; Urbanek et al., 2017) and hydrodynamic patterns make the Arctic an accumulation zone for plastics in the next decades (Cózar et al., 2017). The Arctic could then experience a higher increasing rate of environmental plastic levels than any other parts of the world.

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CRediT authorship contribution statement

France Collard: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Amalie Ask:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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