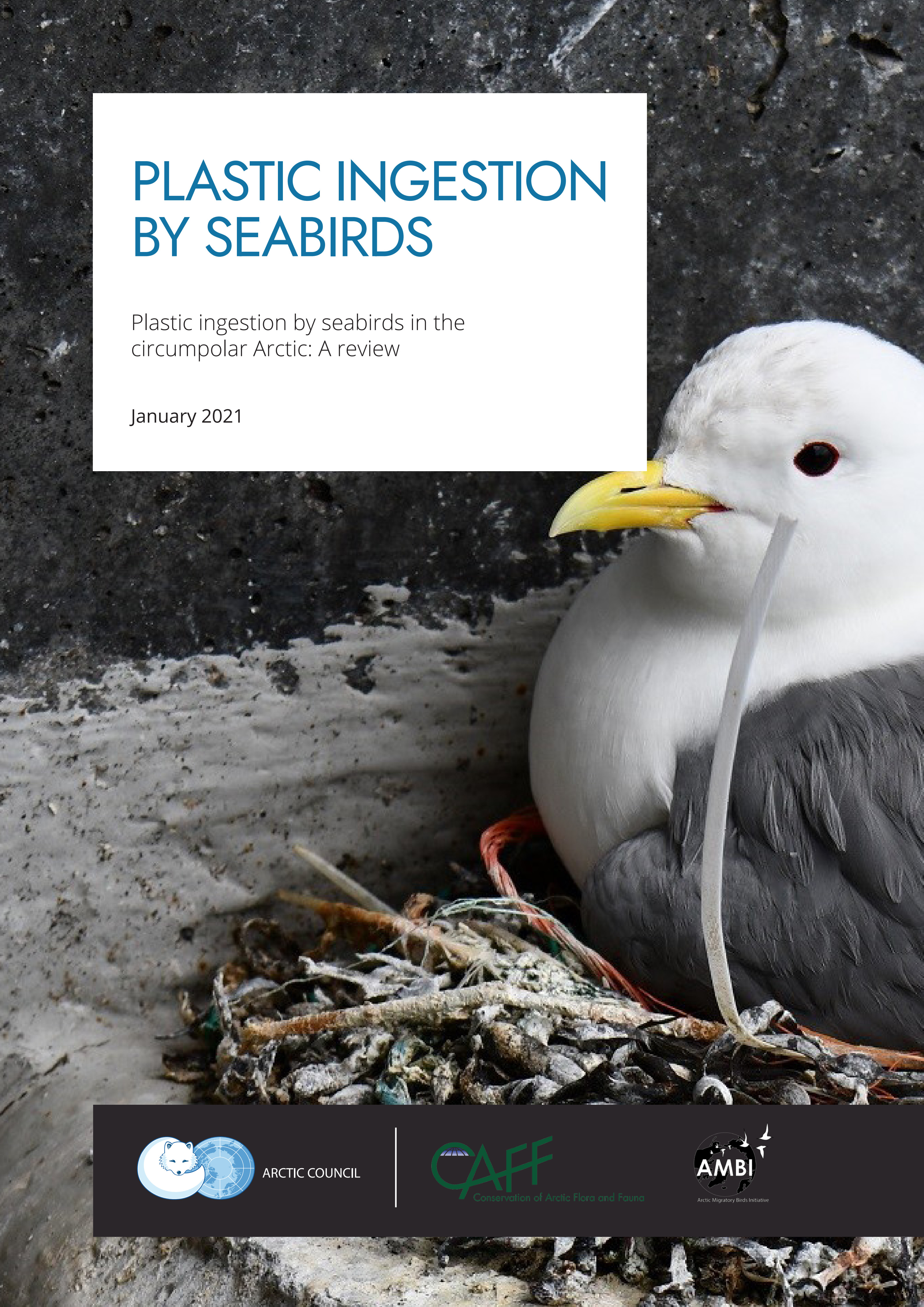

PLASTIC INGESTION BY SEABIRDS

Plastic ingestion by seabirds in the circumpolar Arctic: A review

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ABSTRACT

Plastic pollution is a ubiquitous global environmental problem. Plastic ingestion by seabirds is an increasing issue even in remote areas, such as the Arctic, yet research and monitoring of plastic ingestion in arctic seabird populations is limited and there are large knowledge gaps for many geographic regions. There is currently no standard technique for monitoring plastic debris across the Arctic, making it difficult to compare studies and monitor global trends. Here, we review the current state of knowledge of plastic ingestion by seabirdsin the Arctic. We analyzed 38 published records that report plastic ingestion by seabirds in the Arctic region. Of the 51 seabird species examined for plastic ingestion in the Arctic, over half have ingested plastic, however the majority havea limited number of studies, small sample sizes, and/or data more than 15 years old. Additionally, the spatial distribution of plastic ingestion reports in the Arctic varies widely, with large knowledge gaps in the northernmost areas of most countries. This indicates that we lack recent information on plastic ingestion for the majority of seabird species in the Arctic. Further, less than one third of studies references standardized methods from other regions, making it difficult to assess spatial and temporal trends. Long-term monitoring programs should be established in the Arctic to obtain an accurate assessment of plastic ingestion by seabirds in this region.

Plastic from a Fulmar stomach.
Photograph: Signe Christensen Dalsgaard

INTRODUCTION

Marine debris, such as plastic, is an increasing global environmental concern that is now found in every ocean (UNEP 2016). Marine debrisaffects over 747 wildlife species including marine mammals, fish, sea turtles and seabirds (Kühnand van Franeker 2020). Seabirds are particularly vulnerable to marine plastic, with plastics found in over half ofseabird species worldwide (Kühn and van Franeker 2020). Moreover, seabirds can be useful indicators of marine pollution due to their foraging ecology and high but variable position in the marine food web, thus enabling the monitoring of temporal, geographical and trophic level trends of plastic ingestion (van Franeker et al. 2011). The ingestion of plastic by seabirds mistaking the debris for prey species (Cadée 2002), or acquiring debris through trophic transfer from their prey (Hammer et al. 2016), can result in internal wounds, blockages in the gastrointestinal tract or reduced feeding in the seabird (Laist 1997), transfer of chemicals absorbed to or digested from the plastic (Lu et al. 2019) or physiological effects such as reduced body condition or increased satiation (Auman et al. 1997).

Plastic ingestion by seabirds is an increasing problem even in remote or isolated areas, such as the Arctic and subarctic (Mallory et al. 2006; Provencher et al. 2009). Plastic debris can enter these areas through local sources, such as landfills and fisheries, or from other areas via ocean currents, wind, sea ice or biotransport by seabirds (Mallory 2008; Cózar et al. 2017; Obbard 2018; Halsband and Herzke 2019). As human population, shipping and fishing activity increase in this vast, resource rich area, plastic ingestion by arctic seabirds will increase as well (Provencher et al. 2010; Smith and Stephenson 2013).

The northern fulmar (***Fulmarus glacialis***), distributed across the North Atlantic and Pacific Ocean, is the only arctic seabird that is systematically examined for plastic ingestion through the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) monitoring program in the North Sea (OSPAR 2015). Though based in the North Sea, the OSPAR protocol has been adopted by other countries in the Arctic (e.g. Iceland; Kühn and van Franeker 2012), and northern fulmars have the highest rate of plastic ingestion among northern seabirds that have been examined (Provencher et al. 2009; Bond et al. 2013; Kühn and van Franeker 2020). The first record of plastic debris in a northern fulmar in the subarctic was found by Day (1980) and levels of plastic ingestion innorthernfulmars globally have increasedor remained stable over time (Avery-Gomm et al. 2012; Mallory 2008; Provencher et al. 2009; van Franeker et al. 2011; Trevail et al. 2015).

However, surface feeders such as northern fulmars are not the only seabirds affected by plastic ingestion. Pursuit-diving seabirds that feed below the surface, such as alcids, have also demonstrated plastic ingestion in the Arctic (Provencher et al. 2010). Plastic ingestion has been recorded in common murres (***Uria aalge***) and thick-billed murres (***U. lomvia***), but at lower levels than in northern fulmars in the same area (Day 1980; Robards et al. 1995; Provencher et al. 2010; Bond et al. 2013; Poon et al. 2017). Further, plastic ingestion by murres has remained relatively constant over time in both the Arctic (Baak et al. 2020) and subarctic (Bond et al. 2013). To obtain accurate information on marine ecosystem health, it is important to sample various seabird species as different species forage across different areas and trophic levels (Poon et al. 2017).

Plastic ingestion rates may also differ due to the time of year, morphological differences, foraging range, diet, or the retention times of plastics (Moser and Lee 1992; Provencher et al. 2010, 2014; Avery-Gomm et al. 2013; Ryan 2015; Poon et al. 2017; Kühnand van Franeker 2020). For example, Mallory et al. (2006) and Provencher et al. (2010) found that northern fulmars and thick-billed murres collected earlier in the breeding season had a higher occurrence of plastics, suggesting that some or most of the plastic in birds may have been ingested from other regions during migration. Contrastingly, Vlietstra and Parga (2002) found that short-tailed shearwaters had more plastic during the breeding season than the non-breeding season. Thus, assessing plastic ingestion by seabirds during different times of the breeding and non-breeding period are essential to accurately determine the risk of plastic ingestion for each species in a given region. In terms of morphological differences, procellariiforms have a narrow passage connecting the gizzard and proventriculus and thus do not often regurgitate hard indigestible food items, making them more susceptible to the accumulation of ingested plastic debris in the digestive tract (Carey 2011; Acampora et al. 2014). In contrast, gulls, such as the black-legged kittiwake (***Rissa tridactyla***), often regurgitate hard prey items (e.g. bones) into boluses, and thus are less likely to accumulate plastics (Ryan 1987; Poon et al.2017). This reinforces the need for regular monitoring of indicator species over different spatial and temporal scales.

Despite the need for information on plastic ingestion by seabirds, research and monitoring of plastic ingestion in arctic seabird populations is limited or varies significantly by species and/or region, and there remain large knowledge gaps for many species' habitats and geographic regions (Provencher et al. 2015; O'Hanlon et al. 2017). In addition, there is currently no standard technique for monitoring plastic debris across the Arctic, making it difficult to compare studies and monitor global trends (Provencher et al. 2015). Of the seabird plastic ingestion research that currently exists in the Arctic, few studies use current,standardized methods from other regions (OSPAR 2015; Provencher et al.2017, 2019) and many fail to report important metrics of ingested plastics, such as number, mass, size and colour (O'Hanlon et al. 2017). For example, in the northeastern Atlantic, there are a variety of seabird species, such as black guillemots (***Cepphus grylle***), black-legged kittiwakes, and thick-billed murres, where only one study in the region reports these metrics when reporting plastic occurrence (O'Hanlon et al. 2017). To assess long-term trends of marine plastic in the Arctic region, standardized methods for plastic ingestion research are essential.

> Studying plastic ingestion in seabirds is a useful tool to assess the level of marine debris in the Arctic.

The need for standardized methods for monitoring plastic ingestion by seabirds in the circumpolar Arctic has been highlighted by the Arctic Migratory Birds Initiative (AMBI), a project under the Conservation of Arctic Flora and Fauna (CAFF) working group of the Arctic Council (CAFF 2019). However, many countries lack the studies and knowledge that enable and support standardized long-term monitoring programs. The AMBI 2019-2023 workplan (CAFF 2019) highlights the need for a review of current published information on plastic ingestion by circumpolar seabirds, in order to recommend future research and monitoring programs in the Arctic. The implementation of long-term monitoring programs for marine plastics in the Arctic will facilitate our understanding of the impacts of plastic ingestion on arctic species and ecosystems and allow us to compare plastic ingestion across species, regions and time.

The objective of this paper is to fill this critical knowledge gap related to plastic ingestion by seabirds in the Arctic. To do this, we conducted a literature review of plastic ingestion by seabirds in the Arctic, where we identified knowledge gaps and important indicator species for monitoring plastic ingestion by seabirds in the Arctic. Studying plastic ingestion in seabirds is a useful tool to assess the level of marine debris in the Arctic. This study Studying plastic ingestion in seabirds is a useful tool to assess the level of marine debris in the Arctic. provides a basis for future marine monitoring and management and can be applied to inform future policy and regulations on marine debris in the Arctic region, leading to actions towards habitat protection including pollution prevention.

METHODOLOGY

We used the Web of Science search engine and citation index as our primary literature source between May and December 2019. We used the following search terms: "seabird* plastic* Arctic","seabird* debris Arctic",and "seabird* pollut* Arctic", to determine the level of plastic in seabirds in the circumpolar Arctic. Additionally, we searched all cited references from the papers reviewed for the keywords listed above. Lastly, we consulted all country representatives of the CAFF Circumpolar Seabird Expert Group to add any additional literature on plastic ingestion by seabirds in the Arctic. For the purpose of this review, we restricted our literature search to the Arctic region, defined following CAFF (Irons et al. 2015), which incorporates the physical, geographical and ecological differences in the terrestrial and marine environments in the Arctic and subarctic region such as permafrost, sea ice extent and isotherms (Fig.1). This includes parts of Canada, the United States (Alaska), the Kingdom of Denmark (Greenland and the Faroe Islands), Iceland, Russia, Finland, Sweden and Norway. This literature search included records from 1980 to 2019.

For the purpose of this review, we included all papers, detected using the search terms above,that examined plastic ingestion by seabirds within the CAFF region. We defined seabirds according to Gaston (2004), which includes tubenoses (Procellariiformes), cormorants and gannets (Pelecaniformes), auks, gulls, terns, skuas, and phalaropes (Charadriiformes). Sea ducks and mergansers (Anseriformes; Merginae) and loons (Gaviiformes) were also included because these species spend the majority of the year at sea (Gaston 2004). We collected data on a total of 51 seabird species in the Arctic. In this review, the term "plastic" includes macroplastics (>20-100mm), mesoplastics (>5-20 mm) and microplastics (< 5 mm; Barnes et al. 2009), because not all papers differentiate between size classes and/or report size. Plastics are divided into two categories: industrial plastic (small plastic pellets used in manufacturing) and user plastic (non-industrial plastic from consumer and commercial sources; van Franeker et al. 2006, 2011).

For each study, we recorded the species, location, year of sampling, sampling method and sample size. Additionally, we recorded whether studies reported percentage frequency of occurrence (defined as the number of birds, boluses or regurgitates in a sample that contained plastic, including birds that were examined but did not contain plastic; van Franeker and Meijboom 2002) of plastic ingestion, number of plastic pieces, mean mass, median mass, mass standard deviation or standard error, mass range, and plastic type, size and colour, all of which are metrics suggested by Provencher et al. (2017). We also recorded whether the studies referenced standardized methods outlined in any version of the OSPAR monitoring protocol (e.g. van Franeker 2004; OSPAR 2015) or Provencher et al. (2017), and whether the authors compared plastic between age, sex, or sampling methods. General summary statistics are presented in tabular form. Important indicator species and areas for future research are identified, and future research methods are suggested.

Fig. 1. Map of the circumpolar Arctic as defined by CAFF including an outline of the Arctic circle

RESULTS AND DISCUSSION

We found 38 published articles and reports on plastic ingestion by arctic seabirds (see Supplementary material for full list). The spatial and temporal distribution of reports, metrics of plastic ingestion reported, sampling methods used, and species examined in each studywere examined. Two studies, Day et al. (1985) and Provencher et al. (2014), contained multiple previously unpublished datasets (19 and 11 datasets, respectively). These could not be included in analyses of metrics reported or sampling methods used because the datasets were obtained from a variety of sources, thus not all details (e.g. method of collection) were published.

DISTRIBUTION OF REPORTS

The distribution of reported plastic ingestion by seabirds in the Arctic is demonstrated in Fig. 2. The Canadian Arctic has the highest number of plastic ingestion reports (eight studies, 22%), followed by Russia (19%) and Alaska (17%). Iceland and the Faroe Islands have the lowest (6%) with only two studies each (Kühn and van Franeker 2012; van Franeker 2012; Trevail et al. 2014; Hammer et al. 2016). Following O'Hanlon et al. (2017), the distribution of studies from before and after 2000 was compared (Fig. 2) since this represents the approximate halfway point between the earliest incidence of plastic ingestion reported in this review (sampled in 1969-1977; Day 1980) and the date of publishing. Seabird samples were collected between 1969 and 2015, with 51% of samples collected before 2000.

Spatially, Canada and Alaska have the most studies, but the reports are not evenly distributed along the coasts and much of each country is without data. In Canada, 84% of samples were collected after 2000, but all were from Nunavut and there are no studies in the other two territories in the Arctic; Northwest Territories and Yukon (Fig. 2). Similar to Canada, Alaska has more plastic ingestion reports after 2000 (four versus two), although post-and pre-2000 studies had a similar number of sampling locations (34 and 36, respectively). Also similar to Canada, these data are concentrated in one region, with all studies from the Aleutian Islands and Bering Sea, and no data for northern Alaska (which includes large bodies of water such as the Chukchi Sea and Beaufort Sea). In general, most countries lack data for the northernmost areas in their geographic boundaries (see Fig. 2). This pattern may be partially explained by the uneven distribution of seabird colonies along coastlinesin the Arctic (Irons et al. 2015) and/or the increasing cost of research with increasing latitude (Mallory et al. 2018). Further, neither Finland nor Sweden have coastlines bordering the Arctic Ocean, thus there are no reports for plastic ingestion by seabirds in these countries.

Some areas are not sampled at all, despite the presence of breeding colonies (Irons et al. 2015). For example, in Russia, there are four post-2000 studies (four sampling locations) and three studies from before 2000, but there remains little data for much of the country. Moreover, much of the existing data is published in local sources, written in Russian, and thus is not easily available internationally (e.g. Mikhtaryantz 1981; Turovskaya and Nichkevich 2005; Tolmacheva 2012; Artukhin et al. 2014; Golovnyuk et al. 2019; Solovyeva et al. 2020). While our team included Russian members to help overcome this challenge, it is possible that more data in Russian language sources was not found during this study. Importantly, many known seabird colonies in Russia are not monitored in any capacity (e.g. monitoring programs for population trends and productivity; Irons et al. 2015). In order to obtain an accurate estimation of marine plastic in the circumpolar Arctic, data from these sites are necessary.

Finally, it is important to note that plastic levels in seabirds may not accurately represent the amount of plastic in the location where the seabird was collected. For example, many seabirds have large foraging and/or migratory ranges (e.g. northern fulmars; Mallory et al. 2020). Therefore, depending on the retention times of plastics in the gastrointestinal tract (which are largely unknown for many seabirds; Ryan 2015), plastic in arctic seabirds may be from a variety of foraging or migration sites, and may not represent the amount of plastic in the Arctic at the time of sampling.

Temporally, approximately half of all plastic ingestion reports in the Arctic were published before 2000. For example, in Greenland and Svalbard, all studies except two from each region (Knutsen 2010; Provencher et al. 2014; Trevail et al. 2015; Amelineau et al., 2016) collected samples before 2000, which suggests that plastic assessments are outdated in this area (given the rate of change in knowledge of plastic debris distribution and uptake; Wilcox et al. 2015). This highlights the need for updated studies on species in these areas to assess temporal and spatial trends in plastic ingestion. To do this, information is needed on plastic ingestion in a species over multiple years. For example, at Cape Vera, Nunavut, northern fulmars had no plastic reported in their diet from 1980–1984 (Byers et al. 2010), but this increased to 31% by 2003–2004 (Mallory 2008), and Provencher et al. (2009) showed that frequency of occurrence of plastic in northern fulmars had also increased in Lancaster Sound from 0% in the 1970s to 80% by 2008. Further, Robards et al. (1995) conducted a direct temporal comparison to the results of Day (1980) in Alaska, and found that the number of seabird species that ingested plastic, the frequency of occurrence of plastic in seabirds, and the mean number of plastic pieces ingested by seabirds increased between the two

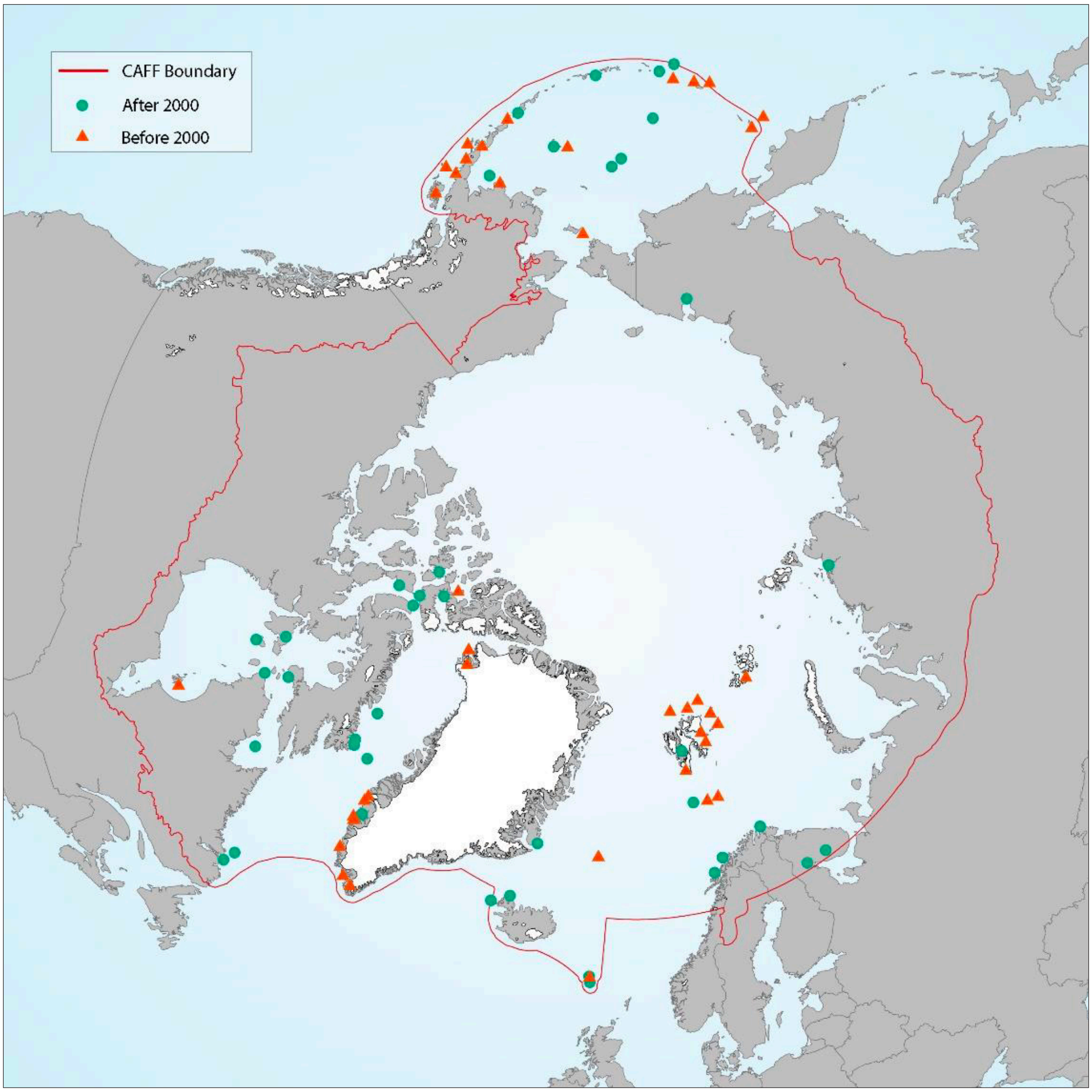

Fig. 2. Distribution of reported plastic ingestion by seabirds in the circumpolar Arctic. Each point represents a sampling location (79 sampling locations across 37 studies*). Overlapping points (i.e. locations sampled more than once) were offset to show all sampling events.
****Data from Day et al. (1985) was not included in this map because specific locations were not given in the text.***

studies. However, since the implementation of The International Convention for the Prevention of Pollution from Ships (MARPOL), the amount of industrial pellets ingested by seabirds from the South Atlantic and Indian Oceans has decreased (Ryan 2008). Similarly, through the OSPAR monitoring program, van Franeker and the SNS Fulmar Study Group (2013) found that the number and mass of industrial pellets ingested by northern fulmars have decreased since the 1980s. Therefore, as human, shipping and fishing activity continue to increase in the Arctic (Smith and Stephenson 2013), assessing temporal trends in plastic ingestion by seabirds will be increasingly important.

Van Franeker and Meijboom (2002) determined that plastic ingestion in northern fulmars should be monitored over four to eight years to obtain an accurate trend of plastic ingestion. Besides the ongoing OSPAR monitoring program in the North Sea (much of which is not within the Arctic as defined by CAFF), no countries have long-term programs in place for annual monitoring of plastic ingestion by seabirds, and thus do not have sufficient data to assess temporal trends. Furthermore, sample collections are often opportunistic. Though opportunistic data are very useful to understand current plastic ingestion levels, monitoring species over time at the same location is required to assess trends of marine plastic in the arctic environment. Thus, where possible, plastic ingestion by seabirds should be monitored using a minimum sample size of 40 individuals across four to eight years (van Franeker and Meijboom 2002).

METRICS REPORTED

To analyse metrics reported, Day et al. (1985) and Provencher et al. (2014) were not included in analysis because these studies published datasets from a variety of sources, thus not all metrics could be assessed. Of the remaining 36 papers examined, 22 (61%) had plastic as the primary objective of the research, whereas the remainder (39%) were diet studies that reported plastics. Frequency of occurrence, also described as prevalence or incidence, of plastic ingestion is the most commonly reported metric in plastic ingestion researchin the Arctic (89% of studies; Table 1). The second most reported metric is the mean number of plastic pieces (63%), followed by plastic type (60%) and mean mass of plastic (51%). Frequency of occurrence and mass of plastic pieces are the most biologically relevant measure of plastic ingestion in terms of impact on the organism (van Franeker and Meijboom 2002; van Franeker et al. 2011). Yet, though average mass was well reported, median mass was the least reported metric (9% of studies). Median values are important to include because they reduce the effect of outliers, thus providing a more representative mass value in a biased dataset (Provencher et al. 2017). Continuing to report these metrics will allow us to accurately compare plastic ingestion in seabirds across spatial and temporal scales.

Similar to what has been reported in O'Hanlon et al. (2017) and Provencher et al. (2017), which cover different geographic regions, most studies did not report the minimum size of plastic pieces. Reporting minimum plastic size is important to understand the size classes examined (e.g. macroplastic, mesoplastic, microplastic) and to determine whether seabirds may be ingesting these items through their prey (i.e. trophic transfer), such as fish or other seabirds (Hammer et al. 2016). For example, in the Faroe Islands, great skua (*Stercorarius skua*) pellets with bird remains contained more plastic than pellets with fish remains (Hammer et al. 2016). Further, great skua pellets containing the remains of northern fulmars had more plastic than pellets with black-legged kittiwake remains (Hammer et al. 2016), which suggests that northern fulmars ingest more plastic than black-legged kittiwakes in that region. This aligns with our results, where northern fulmars ingested more plastic on average than black-legged kittiwakes in the Arctic (see Species examined section and Table 3). Seabirds may be susceptible to plastic ingestion directly from the environment as well as indirectly from prey species (Provencher et al. 2019), thus it is important to record plastic size to help determine how seabirds are ingesting plastic and if there are trophic patterns. However, it should be noted that plastic pieces can break down into smaller pieces once inside the gastrointestinal tract, and thus size of pieces in the gastrointestinal tract may not be representative of the size of pieces that seabirds ingest.

Most studies failed to report data on the colour and size of plastic pieces. Plastic colour was reported in 34% of studies, however, some studies classified colours by light/dark (e.g. Amélineau et al. 2016), while others classified colours into eight main colour categories (e.g. Avery-Gomm et al. 2018). These differences make results incomparable across studies. Colour is an important metric to report as it may further our understanding of how species with different foraging strategies select plastics (Santos et al. 2016). However, if there are no data on the availability of plastic colours in the marine environment, we are unable to determine if plastic ingested by seabirds reflects selectivity or the availability in the marine environment. Nonetheless, standardized methods for colour classification should be used to facilitate comparisons across studies (see Provencher et al. 2017).

Photograph: Jenn Provencher

Photograph: Mark Mallory

Plastic type is important to report to help identify the sources of plastic in the marine environment. Plastic type was recorded in 60% of studies, however, the method of reporting varied widely. Some studies did not categorize plastics further than user and industrial plastics (e.g. Vlietstra and Parga 2002) while others sorted user plastics into sub-categories (e.g. fragments, sheet-like plastics, threadlike plastics; Avery-Gomm et al. 2018). However, of the studies that sorted user plastic into sub-categories, some used the standardized definitions from van Franeker et al. (2011) and OSPAR (2015) (e.g. Poon et al. 2017), while others did not (e.g. Mallory et al. 2006). Additionally, some studies categorized plastics by polymer type (e.g. polyethylene, polypropylene, polystyrene; Yamashita et al. 2011). The large variation in the categorization of plastic type makes it difficult to compare results across studies. Standardized methods to classify plastic type (van Franeker et al. 2011) must be employed in order to further our understanding of the sources of marine plastic in the Arctic as well as the types of plastic that seabirds are most susceptible to ingesting.

Overall, 28% of the 36 studies used standardized methods from other regions in some form (compared to less than 25% globally; Provencher et al. 2017). The first standardized protocol for plastic ingestion monitoring in seabirds was the OSPAR monitoring programin the North Sea, published by van Franeker (2004). Since then, 10 (48%) studies on plastic ingestion by seabirds in the Arctic reference a version of this protocol. Of the two studies published since the 2017 standardized methods recommendations by Provencher et al. (2017), both use these methods and the OSPAR monitoring protocol (Avery-Gomm et al. 2018; Provencher et al. 2018). However, these protocols were developed for other regions and some Arctic countries cannot adopt these methods. Thus, standardized methods for plastic ingestion research for the Arctic should be developed, in line with protocols from other regions, to facilitate comparisons across the Arctic and worldwide.

Finally, three studies examined the difference in plastic ingestion between ages, where one study (Avery-Gomm et al. 2018) found no significant difference between ages and two studies (Day 1980; van Franeker 2012) found that juvenile or subadult seabirds ingest more plastic than adults. Five studies examined differences in plastic ingestion between sexes and found no significant difference (Day 1980; Vlietstra and Parga 2002; Trevail et al. 2015; Poon etal. 2017; Avery-Gomm et al. 2018).

SAMPLING METHODS

Following Provencher et al. (2017), the sampling method of each paper was recorded (Table 2). Three studies (8%) did not specify sampling methods. Necropsy of the gastrointestinal tract is the most common sampling method used to examine plastic ingestion by seabirds in the Arctic (similar toProvencher et al. 2017), where 90% of samples were necropsied. The majority examined the stomach (proventriculus and gizzard) and one study (Provencher et al. 2018) examined faecal precursors (cloaca and portion of the small intestine). Of necropsied birds, the collection of beached birds was the most common sampling method (18%), followed by bycatch (13%).

The other main sampling method used in the Arctic is the collection of food remains (23% of studies; Table 2). Of the food remains collected, bolus samples (naturally regurgitated indigestible prey items found at breeding sites) were the most commonly collected (18%), followed by regurgitates (natural regurgitation or stomach pumping; 5%).

The advantages and disadvantages of each collection method are explained in detail in Dehnhard et al. (2019) and Provencher et al. (2017 and 2019). Briefly, necropsy is the most accurate assessment of plastic ingestion and has several benefits over other methods, including the ability to determine age, sex, body condition, and potential plastic-related contaminants in tissues (van Franeker et al. 2011; Trevail et al. 2014; Herzke et al. 2016; Provencher et al. 2019). However, necropsy can be lethal (e.g. legal hunting) and other collection methods (e.g. beached versus bycatch) may result in different levels of plastic ingestion (Ryan 1987; Provencher et al. 2017). On the other hand, bolus and regurgitate samples are relatively non-lethal (but can be lethal, see Provencher et al. 2017) and can be regularly collected, but may not accurately represent the amount of plastic ingested by the seabird as some contents of the stomach may not be obtained (e.g. plastics trapped in the gizzard in Procellariforms; Hammer et al. 2016; Provencher et al. 2019; Kühn and van Franeker 2020). However, bolus samples can be collected when researchers visit seabird colonies for other monitoring purposes. For example, over one third of the studies we reviewed had collected data for diet studies and subsequently published information on plastics. Thus, each sampling method has strengths and weaknesses but should always be meticulously reported for easy comparison.

Three studies in this review reported multiple collection methods, but none compared results between methods. Comparing sampling methods is important to determine if sampling method influences the level of plastics in seabirds (i.e. method bias), especially since there remains debate on this topic (Ryan 1987; Provencher et al. 2017). For example, Kühn and van Franeker (2020) determined that plastic levels do not differ between sampling methods in gulls, skuas and cormorants, but that petrels and albatrosses have higher plastic levels when necropsy is performed than when regurgitates are examined. However, van Franeker and Meijboom (2002) found no difference in beached versus bycatch northern fulmars in the North Sea. Thus, when multiple sampling methods are used, data should be compared between methods.

SPECIES EXAMINED

Within the circumpolar Arctic, plastic ingestion has been examined in 51 arctic breeding or migratory seabird species (Table 3, see also Table S1). The northern fulmar is the most widely studied species appearing in 71 %of studies, followed by the thick-billed murre in 37% of studies. Overall, 28 (54%) species had ≤ 2 studies in the literature, and 56% of species have only been examined in one country.

We found that 27 of the 51 (53%) species examined in the Arctic had ingested plastics. This number is lower than the North Atlantic, where 25 of 34 (74%) examined species have ingested plastics (O'Hanlon et al 2017). In terms of frequency of occurrence of plastic ingestion, only one species, the great shearwater (***Puffinus gravis***), did not have a frequency of occurrence value reported (only presence/absence was recorded; M.S.W. Bradstreet unpubl. in Day et al. 1985). Of the remaining 50 species that had at least one reported frequency of occurrence value, the species with the highest mean frequency of occurrence was the fork-tailed storm-petrel (***Oceanodroma furcata***) with 93% (three studies, average individuals sampled = 14; Day1980; Day et al. 1985; Robards et al.1995) followed by the short-tailed shearwater (***Puffinus tenuirostris***) with 92% (eight studies, average individuals sampled= 72; Day 1980; Robards et al. 1995; Vlietstra and Parga 2002; Yamashita et al. 2011; Tanaka et al. 2013; Artukhin et al. 2014; Golovnyuk etal. 2019; Solovyeva et al. 2020). Twenty-nine (57%) species had a mean 0% frequency of plastic ingestion. However, of these, 76% had an average sample size of individuals < 40, the recommended number of samples for plastic ingestion research in northern fulmars per year and area (van Franeker and Meijboom 2002).

The CAFF Circumpolar Seabird Monitoring Plan (Irons et al. 2015) defines arctic-breeding seabirds as seabirds that breed entirely within the boundaries of the CAFF region (30 species) or that breed partly within these boundaries but also breed in more southern regions (34 species), and thus determined that there are 64 seabird species that breed in the Arctic (Table S2). Though 51 seabird species have been examined for plastic ingestion in the Arctic, only 40 of these are defined as seabirds by Irons et al.

2015 (the remaining 11 are considered migratory). Of these 40,23 (58%) have incidences of plastic ingestionin the Arctic greater than zero. However, 63% have not been examined after 2000and 45% do not have any study with a sample size larger than 40 individuals.

The seabird group with the highest frequency of plastic ingestion was the Procellariiformes. The three procellariform species with the highest incidences of plastic ingestion were the fork-tailed storm petrel, short-tailed shearwater (***Puffinus tenuirostris***) and northern fulmar, with an average prevalence of 93%, 92% and 58%, respectively. Even though sample sizes for the fork-tailed storm petrel were small (maximum individuals = 21), the high prevalence of plastics suggests this speciesis at high risk for plastic ingestion in the Arctic. These results are similar to other regions, where procellariiforms had higher rates of plastic ingestion than other seabird groups (Ryan 1987; Moser and Lee 1992; Gilbert et al. 2016; O'Hanlon et al. 2017; Provencher et al. 2017). Procellariiforms are surface-feeding seabirds and given the volume of plastic debris floating in the Arctic Ocean (Cózar et 11al. 2017), these seabirds are more likely to be exposed to plastic than other pursuit-diving seabirds (Provencher et al. 2014, 2017; O'Hanlon et al. 2017).

Auks (Alcidae) are pursuit-diving seabirds that catch and swallow their prey underwater (Gaston and Hipfner 2000) and thus should be at less risk of ingesting plastics. As expected, auks had lower plastic ingestion rates than surface-feeding procellariiforms, similar to the North Atlantic (O'Hanlon et al. 2017) and North Pacific (Avery-Gomm et al. 2013), but results varied widely (ranging from 0-100%; see Supplementary material). For example, parakeet auklets (***Aethia psittacula***) had a mean frequency of occurrence of 67%, whereas thick-billed murres and black guillemots had an average frequency of occurrence of 3% and 0%, respectively. The variability in plastic ingestion by auks may be explained by differences in diet. Thick-billed murres and black guillemots mainly consume fish or crustaceans (Gaston and Hipfner 2000; Butler and Buckley 2002), whereas parakeet auklets largely feed on small copepods and amphipods (Jones et al. 2001). Thus, small plastic pieces may be mistaken for zooplankton in the water column (Amélineau et al. 2016).

Similar to auks, gulls (Laridae) have lower plastic ingestion rates (0 to 27%) compared to procellariforms. Of the nine species of gulls examined for plastic ingestion in the Arctic, only three, the herring gull (***Larus argentatus***), black-legged kittiwake, and glaucous-winged gull (***Larus glaucescens***), have average sample sizes >40 (see Table 3). These species have an average frequency of occurrence of 10%, 6% and 0%, respectively, suggesting that gulls are at a low risk of plastic ingestion in the Arctic. It is important to note that glaucous-winged gulls have not been examined in the Arctic since before 2000, and elsewhere, have higher incidences of plastic ingestion (e.g. 33% in the North Pacific; Avery-Gomm et al. 2013), indicating that plastic ingestion by gulls in the Arctic merits further study. Overall, the lower levels of plastic ingestion in gulls may be explained by a gull's ability to regurgitate indigestible food items (Ryan 1987; Carey 2011). Comparatively, gulls in southern areas have varying levels of plastic ingestion, which can be attributed to the proximity to anthropogenic sources of plastic pollution (Seif et al. 2018). As human population, shipping and fishing activity increase in the Arctic region (Smith and Stephenson 2013), the risk of plastic ingestion by gulls may increase.

Terns (***Sternidae***) have a plunge-diving foraging strategy where they pursue individual prey (Nisbet et al. 2017), and therefore should be less likely to accidentally ingest

Steller's Eider. Photograph: Mark Wilson

plastics. Thus, as expected, terns have no incidences of ingested plastic in the Arctic. Of the six tern species that breed in the Arctic (Irons et al. 2015), only two have been assessed for plastic ingestion and only one study (Provencher et al. 2014) has a sample size of > 40. In other regions, terns have little to no plastic ingestion (Moser and Lee 1992), suggesting that this group is at less risk of plastic ingestion.

In skuas (Stercorariidae), though four species of skua have been examined for plastic ingestion in the Arctic, only one, the great skua, had a sample size > 3 (Knutsen 2010; Hammer et al. 2016). The average frequency of occurrence for this species was low (4%, average sample size= 692; Knutsen 2010; Hammer et al. 2016), suggesting this species is at a low risk of plastic ingestion, which is consistent with great skuas in the North Atlantic (O'Hanlon et al. 2017) and skua species across the globe (Kühn and van Franeker 2020).

The only phalarope (Scolopacidae) examined for plastic ingestion in the Arctic region was the red-necked phalarope (or northern phalarope, ***Phalaropus lobatus***), where one study (Day 1980) found a 67% frequency of occurrence of plastic, but this was based on only three samples that were collected prior to 2000. Based on research elsewhere (Moser and Lee 1992; Drever et al. 2018) phalaropes may be at a high risk of plastic ingestion. Though phalaropes are not considered arctic seabirds as defined by CAFF (Irons et al. 2015), their breeding distribution is almost exclusively within the Arctic and subarctic region (Rubega et al. 2000; Tracy et al. 2002). Thus, additional studies on this group may be warranted despite their classification.

There are few studies on Pelecaniformes in the Arctic. For cormorants (Phalacrocoracidae), two studies (Day 1980; Robards et al. 1995) examined three species of cormorants in Alaska for plastic ingestion, both of which were conducted before 2000. Of these, no sample size exceeded 16 birds and only two pelagic cormorants (***Phalacrocorax pelagicus***) had plastics present. These results are similar to plastic ingestion levels in cormorants elsewhere, for example, in the North Atlantic, the great cormorant (***P. carbo***) and the European shag (***P.aristotelis***) have a 3% and 5% mean frequency of occurrence, respectively (O'Hanlon et al.2017). In the case of gannets (Sulidae), there are no data on the plastic ingestion by the northern gannet in the Arctic. There are limited data on plastic ingestion by the northern gannet globally, though gannets appear to have relatively low incidences of plastic ingestionin the North Atlantic (Moser andLee 1992; O'Hanlon et al. 2017). However, cormorants and gannets are known to incorporate plastics into their nests (Podolsky and Kress 1989; Votier et al. 2011; O'Hanlon et al. 2017), thus these species may be better suited for research on nest incorporation of plastics.

Lastly, sea ducks (Anseriformes) appear to be at low risk of plastic ingestion. All sea ducks had little to no plastic ingestion (see Table 3), similar to sea ducks in the North Pacific (Avery-Gomm et al. 2013), but the only species withmultiple studies and adequate sample sizes was the common eider (eight studies across four countries, meansample size= 25). Of the 998 eiders sampled in total, only one contained plastics, suggesting this species is at low risk of plastic ingestion in the Arctic. However, sea ducks can still ingest plastic below the surface and in their prey (English et al. 2015; Tavares et al. 2017). In the Arctic, microplastics have been found in benthic organisms (Fang et al. 2018), which may explain the few incidences of plastic in benthic-feeding sea ducks.

FUTURE MONITORING OF PLASTIC INGESTION BY ARCTIC SEABIRDS

Our review suggests that plastic ingestion by seabirds is widespread in the Arctic. However, we know relatively little about plastic ingestion in many arctic seabirds and there remain considerable gaps in spatial and temporal information. Further, studies often have small sample sizes or fail to report important metrics of plastic ingestion, making it difficult to compare studies across regions and time. Below we provide suggestions for future monitoring of spatial and temporal trends plastic ingestion by seabirds in the Arcticthat specifically build on the existing data on from the region.

Overall, the most common seabird monitored was the northern fulmar, as found in O'Hanlon et al. (2017) and Provencher et al. (2017), with 27 studies across seven countries in the Arctic. This is likely due to its broad distribution in the Arctic (Mallory et al. 2012) as well as the OSPAR monitoring program (OSPAR 2015), which though focused in the North Sea, has been adapted elsewhere in the Arctic (e.g. Iceland; Kühn and van Franeker 2012). With a circumpolar distribution and high prevalence of ingested plastics (Mallory et al. 2012), northern fulmars are the key indicator for marine plastics in the Arctic and across the northern hemisphere. However, not all countriesin the Arctic will have plastic ingestion data for northern fulmars. For example, the northern fulmar has a relatively limited nesting range in Russia and is only found in the west and east of the Russian Arctic (Mallory et al. 2012). Moreover, most nesting colonies are not accessible for monitoring and sampling (M. V. Gavrilo, pers. comm.), thus northern fulmars are subject to few studies in this country. This indicates that northern fulmars are not a useful indicator of marine plastics throughout the Russian Arctic. Thick-billed murres and black-legged kittiwakes, however, have a larger breeding distribution in Russia, are subject to monitoring at several sites, and are among the second and third most studied species for plastic ingestion in the Arctic. These species can thus be used as additional tools to track trends in plastic pollution over time and space in the Arctic. To obtain accurate information on the distribution of plastics in the marine environment, it is important to sample various seabird species because different species forage across different areas and trophic levels (Poon et al. 2017). Therefore, the northern fulmar, thick-billed murre and black-legged kittiwake should be used as indicators of marine plastic in the Arctic in order to make data more comparable across regions.

Future publications examining plastic ingestion by seabirds should use established standardized protocols (van Franeker et al. 2011; OSPAR 2015; Provencher et al. 2017, 2019). Studies should follow dissection and classification procedures outlined in OSPAR (2015) and van Franeker et al. (2011), report all metrics for plastic ingestion outlined in Provencher et al. (2017), and follow standardized methods for data collection, analysis and presentation in Provencher et al. (2019), depending on the sampling method used. These standardized methods are also important in studies that do not focus on plastic. For example, if seabirds are dissected for a diet or contaminant study (e.g. Hansen et al. 2020), efforts should be made to report the presence or absence of plastic (with plastic ingestion metrics; Provencher et al. 2017) within the body of the paper to make data accessible during literature searches.

Along with standardized methods, where possible, efforts should be made to make information available across languages. For example, plastic ingestion research is increasing in Russia (e.g. Golovnyuk et al. 2019; Solovyeva et al. 2020), but these records are largely inaccessible to many due to language barriers, and vice versa with publications in English. Further, many seabird species are harvested for consumption in the Arctic by Indigenous people, but information is not often made available in local languages. Therefore, translations of main findings should be made accessible across arctic languages to increase our understanding of plastic ingestion by seabirds in the Arcticand increase knowledge mobilization on the subject.

Studies should have an adequate sample size that will allow for spatial and temporal comparisons of plastic ingestion by the species examined. This minimum sample size will change depending on the species, frequency of occurrence of plastics and location of sampling (Provencher et al. 2015, 2017). For example, van Franeker and Meijboom (2002) recommend sampling > 40 northern fulmars in the North Sea in order to have statistical power to examine changes in plastic ingestion over time, whereas in the Canadian Arctic, as many as 80 northern fulmars are needed (Provencher et al. 2015). Thus, it is important that minimum samples sizes for species in a given region are determined, where possible, so samples can be collected accordingly. However, if the minimum sample size is unknown, we suggesta minimum sample size of 40 following van Franeker and Meijboom (2002). Collecting adequate sample sizes will allow us to assess differences in plastic ingestion between species and to monitor temporal trends of plastic ingestion by arctic seabirds.

In order to accomplish the above suggestions, long-term monitoring programs such as the OSPAR monitoring program (OSPAR 2015) should be established acrossthe Arctic. This will allow us to compare studies across spatial and temporal scales while fulfilling current knowledge gaps. For example, we have highlighted areas in the Arctic that have outdated plastic ingestion data (e.g. Alaska, Svalbard, Greenland) and areas that have little or no data (e.g. Russia, northern Alaska, western Canadian Arctic). To obtain an accurate assessment of plastic ingestion by seabirds in the Arctic, future studies in these areas are needed. Since many seabird colonies in the Arctic are currently being monitored for other research (e.g. diet and contaminant studies), we suggest that plastics research is added onto current monitoring programs where possible. Furthermore, long-term monitoring programs should be established in the regions that have already been monitoring plastic ingestion in seabirds over time, to continue estimating temporal trends in marine plastic in the Arctic region.

CONCLUSIONS

Plastic pollution is a global environmental issue that affects a wide range of wildlife species (UNEP 2016)and is increasing even in remote areas, such as the Arctic (Mallory et al. 2006; Provencher et al. 2009). As human activities continue to increase in the Arctic, marine biota will be at a greater risk of ingesting plastic (Provencher et al. 2010; Smith and Stephenson 2013). This review suggests that plastic ingestion by seabirds is widespread in the Arctic, where over half of arctic seabirds examined have incidences of plastic ingestion. However, we know relatively little about plastic ingestion in many arctic seabirds, and there remain considerable gaps in spatial and temporal information. Further, studies often have small sample sizes or fail to report important metrics of plastic ingestion, making it difficult to compare studies across regions and time. Thus, it is important to continue monitoring seabirds as indicators of marine plastics to assess global trends and risks to arctic seabird populations (Avery-Gomm et al. 2012). However, given the increasing number of studies on plastic ingestion by seabirds, standardized methods (e.g. OSPAR 2015; Provencher et al. 2017, 2019) are needed to compare studies spatially and temporally. When data are collected and analysedusing standardized methods, it will not only improve our ability to understandthe distribution of plastic in the marine environment, but also allow us to assess trends in marine plastic on a global scale.

Photograph: Nina Dehnhard

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