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Monitoring litter and microplastics in Arctic mammals and birds

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Abstract

Plastic pollution has been reported to affect Arctic mammals and birds. There are strengths and limitations to monitoring litter and microplastics using Arctic mammals and birds. One strength is the direct use of these data to understand the potential impacts on Arctic biodiversity as well as effects on human health, if selected species are consumed. Monitoring programs must be practically designed with all purposes in mind, and a spectrum of approaches and species will be required. Spatial and temporal trends of plastic pollution can be built on the information obtained from studies on northern fulmars (*Fulmarus glacialis* (Linnaeus, 1761)), a species that is an environmental indicator. To increase our understanding of the potential implications for human health, the species and locations chosen for monitoring should be selected based on the priorities of local communities. Monitoring programs under development should examine species for population level impacts in Arctic mammals and birds. Mammals and birds can be useful in source and surveillance monitoring via locally designed monitoring programs. We recommend future programs consider a range of monitoring objectives with mammals and birds as part of the suite of tools for monitoring litter and microplastics, plastic chemical additives, and effects, and for understanding sources.

Key words: marine litter, debris, plastic, wild food, contamination

Résumé

La pollution plastique a été signalée comme affectant les mammifères et les oiseaux de l'Arctique. La surveillance des déchets et des microplastiques au moyen des mammifères et des oiseaux de l'Arctique présente des avantages et des inconvénients. L'un des points forts consiste en l'utilisation directe de ces données pour comprendre les impacts potentiels sur la biodiversité de l'Arctique ainsi que les effets sur la santé humaine, si les espèces sélectionnées sont consommées. Les programmes de surveillance doivent être conçus de manière pratique en gardant à l'esprit tous les objectifs, et un éventail d'approches et d'espèces sera nécessaire. Les tendances spatiales et temporelles de la pollution plastique peuvent s'appuyer sur les informations obtenues à partir d'études sur les fulmars boréaux (*Fulmarus glacialis* (Linnaeus, 1761)), une espèce qui constitue un indicateur environnemental. Pour mieux comprendre les implications potentielles pour la santé humaine, les espèces et les lieux choisis pour la surveillance doivent être sélectionnés en fonction des priorités des communautés locales. Les programmes de surveillance en cours d'élaboration devraient examiner les espèces pour déterminer les impacts au niveau des populations chez les mammifères et les oiseaux de l'Arctique. Les mammifères et les oiseaux peuvent être utiles pour la surveillance des sources et du suivi au moyen de programmes conçus localement. Les auteurs recommandent que les futurs programmes prennent en compte une gamme d'objectifs de surveillance avec les mammifères et les oiseaux comme faisant partie d'une suite d'outils pour surveiller les déchets et les microplastiques, les additifs chimiques plastiques et leurs effets, et pour en comprendre les sources. [Traduit par la Rédaction]

Mots-clés : déchet marin, débris, plastique, aliment sauvage, contamination

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Introduction

Plastic pollution is a complex anthropogenic threat to global ecosystems (MacLeod et al. 2021). The prolific growth in the production and application of plastic materials is mirrored by increasing amounts of plastics contaminating the environment (Rochman et al. 2013). Plastic materials are diverse, including many different polymers and added chemicals, with resulting differences in environmental stability and physical–chemical properties, which in turn likely have different and uneven effects on environments, animals, and potentially, human health (Shaxson 2009; Brachner et al. 2020; Prata et al. 2021; Thomas et al. 2021). Characterizing the types, sizes, sources, abundance, and distribution of plastics in different environmental compartments is essential for understanding processes and determining risks as well as initiating, and evaluating, mitigation, and remediation options (e.g., Harris et al. 2021).

Large to microscopic pieces of plastics have been observed in all ecosystems on Earth, from populated urban areas to remote islands, deserts, mountains, the depths of the oceans, and polar regions. Plastic pollution is an additional stressor in Arctic ecosystems (Halsband and Herzke 2019; Kumar et al. 2021), which experience a combination of anthropogenic pressures related to climate change, contaminants, and other human impacts, including increasing surface temperatures (Fyfe et al. 2013), rising sea level (Zemp et al. 2019), and invasive species (Goldsmit et al. 2018). Recent work from the Antarctic has demonstrated that polar marine ecosystems may have a greater sensitivity to plastic pollution due to additional stress experienced through ocean acidification (Rowlands et al. 2021).

Monitoring of plastics in the Arctic has been limited and scattered, with focus mostly on areas close to settlements, fishing activities, or on studies in tandem with research on other Arctic stressors. A plan for systematic monitoring of plastics in the Arctic has now been developed, and Arctic States are encouraged to establish holistic monitoring programs (AMAP 2021*b*). Litter and microplastics (<5 mm) have been observed in several abiotic compartments of the Arctic, including seawater (e.g., Lusher et al. 2015), beach sediments (e.g., Bergmann et al. 2017), benthic sediments (e.g., Ramasamy et al. 2021), snow samples (e.g., Bergmann et al. 2019), and sea ice (e.g., Kanhai et al. 2020), as well as Arctic wildlife (e.g., Collard and Ask 2021). Given the widespread occurrence of litter and microplastics in the Arctic, the consequences for biota have become an emerging concern (e.g., Baak et al. 2020*a*; Collard and Ask 2021). It is also important to consider the Arctic within the global context of monitoring litter and microplastics. Currently, a plastic pollution agreement is under consideration by the United Nations, and as this progresses, it will be critical to (a) connect monitoring initiatives across the globe and (b) understand the role of the Arctic in global monitoring efforts (e.g., as a potential baseline/reference site and a potential sink region for plastics).

Mammals and birds are affected by plastic pollution and other anthropogenic litter in two main ways. First, mammals and birds can become entangled in large items of debris on land and in aquatic environments. Entanglement in derelict fishing gear is by far the most reported interaction for aquatic mammals and birds, with consequences ranging from lesions to death by drowning when animals are unable to surface to breathe, or starvation if they are unable to move (NOAA 2014; Panti et al. 2019; AMAP 2021*a*). Reindeer and caribou (*Rangifer tarandus* (Linnaeus, 1758)) have also been observed entangled in derelict fishing gear and other marine litter (e.g., Bergmann et al. 2017; Liboiron et al. 2020). Second, mammals and birds can be affected by plastic pollution through their diet. Ingestion of plastic and other litter items can have a range of deleterious consequences on mammals and birds, including blockage or damage to the digestive tract, which can lead to malnutrition and ultimately death (Kühn et al. 2015; Kühn and van Franeker 2020). Further, high levels of plastic ingestion have been posited to lead to the transfer of chemicals associated with ingested litter (Fossi et al. 2012; Tanaka et al. 2019; Neumann et al. 2021; Routti et al. 2021), though the literature remains inconclusive as to the role of plastics as a primary vector for contaminant transfer (Hamilton et al. In press). Important, chemicals associated with plastics include additives which are introduced during the production of the material, as well as contaminants which are sorbed from the environment (Teuten et al. 2007; Tanaka et al. 2013; Tanaka et al. 2020). To date, much of the information on the impacts of plastics on mammals and birds relates to individual-level rather than population-level effects (Senko et al. 2020).

Indigenous and northern communities, and ecosystems in the Arctic, are uniquely affected by plastic pollution. Arctic ecosystems typically support biota with low growth rates, and habitats are known to be sinks for many contaminants (Dietz et al. 2019; Rigét et al. 2019). The impact of plastics on Arctic wildlife is largely unpublished, including potential effects on wild food. Arctic animals, including mammals and birds, are also integral parts of Arctic human food webs and cultures across the pan-Arctic region, including their key roles in subsistence hunting and traditional diets (Ford 2009; Nunatsiavut Government 2017). Access to healthy wild food such as mammals and birds is thus crucial to both food security (access to affordable healthy food) and food sovereignty (access to culturally important food) for many Arctic peoples (Kinloch et al. 1992; Ford 2009; Nunatsiavut Government 2017). Indeed, the United Nations Declaration of the Rights of Indigenous Peoples states that Indigenous peoples have the right "to be secure in the enjoyment of their own means of subsistence and development, and to engage freely

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in all their traditional … activities", including the hunting and eating of safe wild food (UN 2008). When Indigenous people cannot eat food because of contamination, it interferes with the "the right to maintain, control, protect and develop their cultural heritage, traditional knowledge and traditional cultural expressions, as well as the manifestations of their sciences" (UN 2008; Hoover 2013). Thus, plastic monitoring programs in mammals and birds in the Arctic must be understood in relation to public health and Indigenous rights, and particularly that scientific findings not only impact the scientific community and policy, but also Indigenous peoples.

There is also a need to monitor the effects of plastic pollution on biota in the context of conservation and biodiversity. Across the globe, biodiversity is experiencing a range of threats that are affecting marine, terrestrial, and aquatic ecosystems (Mazor et al. 2018; McElwee et al. 2020). Beyond the monitoring of plastic pollution via biota as an environmental indicator, there is a need to consider monitoring the effects of plastic pollution on biota. This is particularly important in regions where animals are experiencing multiple stressors such as climate change and habitat degradation. While litter and plastic pollution may not be a singular driver of population or species declines (e.g., Bucci et al. 2020), the application of a harm reduction approach to wildlife health and conservation (Stephen et al. 2018; Parkes 2021) can focus on reducing the effects of this stressor, which can be tackled through reduction and mitigation efforts.

The objective of this article is to present the current state of knowledge with regards to litter and microplastics in mammals and birds specifically in the context of discussing opportunities, obstacles, and limitations to using mammals and birds to monitor litter and microplastics in the Arctic, as programs are currently being developed in the region. We aim to provide suggestions for monitoring and research on litter and microplastic in mammals and birds to improve our understanding of the fate and effects of litter and microplastics in the Arctic. The short-term goal of this article is to identify priority areas where immediate activities may progress the field. The long-term goal is to outline a systematic monitoring of plastics in mammals and birds of the Arctic that responds to the needs of both the international scientific community, and of Arctic peoples and governments.

Global state of knowledge on mammal and bird interactions with litter and microplastics

Evidence of litter and microplastic impacts on mammals and birds is available from a variety of international sources. Amongst marine mammals, studies date back to the early 1960s with plastic items and other macrolitter reported as entanglement and ingestion hazards, including baleen whales, beaked whales, dolphins, porpoises, and seals (Caldwell and Golley 1965; Hofmeyr and Bester 2002; Bergmann et al. 2017; Panti et al. 2019). As of 2018, 11 out of the 14 families of cetaceans (86 species) had records of impacts from marine litter (Fossi et al. 2018; Kühn and van Franeker 2020). On a global scale, 40% of marine mammal species have at least one documented occurrence of entanglement, and 56% have at least one documented occurrence of ingestion (Baulch and Perry 2014; Kühn et al. 2015; Kühn and van Franeker 2020). This includes species with different feeding habits and mechanisms (Panti et al. 2019).

Plastics are reported in digestive tracts of marine mammals, and in some cases, have been attributed to an individual's cause of death (reviewed by Kühn and van Franeker 2020). There are high geographic, intraspecific and interspecific variations in ingestion rates (Baulch and Perry 2014). Globally, there have been several studies examining ingested marine litter in seals (Bravo Rebolledo et al. 2013; Denuncio et al. 2017; Donohue et al. 2019; Hernandez-Milian et al. 2019; Bourdages et al. 2020; Perez-Venegas et al. 2021; Pinzone et al. 2021; Wang et al. 2021). With one exception, none of these studies were the result of specific monitoring activities for litter and microplastics. Rather, they were research projects or reports produced by strandings networks, or other opportunistic collection of samples from research programs with a different purpose (e.g., beach cleaning networks and tracking chemical contaminants in mammals). For this reason, much of the impacts on mammals are reported at the individual level rather than at the population level.

Globally, terrestrial mammals have received far less attention in relation to interactions with litter and microplastics to date (Table 1). A recent report by the United Nations Convention on Migratory Species highlights reports of large cats, elephants, and free-ranging cattle all foraging and ingesting plastics (CMS 2021). Camels in the United Arab Emirates had ingested relatively high levels of debris, which likely led to their deaths (Eriksen et al. 2021). These examples illustrate that a diverse suite of mammals all over the world ingest and accumulate plastic pollution.

Reports of ingestion of nonplastic debris by birds dates back to the 1800s, whilst plastic ingestion by seabirds has been reported since the 1960s (Harris and Wanless 1994; Kühn et al. 2015; Provencher et al. 2017). To date, ingestion of plastics or other debris has been reported in 180 of the world's 409 seabird species (Kühn and van Franeker 2020). Of the 64 seabird species in the Arctic, 40 have been examined for ingested plastics in the published literature (Baak et al. 2020*a*). For 58% of these, the ingestion of plastic was documented. For the most part, the species selected for these studies were chosen either opportunistically or in relation to other scientific studies rather than through priorities related to local food webs, though this is changing (Liboiron et al. 2020). There are also some examples of trophic transfer of ingested plastic in birds (Ryan and Fraser 1988; Hammer et al. 2016; Álvarez et al. 2018).

While several studies suggest that seabirds and mammals experience negative effects from ingested plastic pollution at the individual level, studies to assess the impacts of plastic pollution at the population level are needed but remain a challenge (Lavers and Bond 2016; Lavers et al. 2019; Senko et al. 2020). Like mammals, seabirds are also impacted by entanglement, with 27% of the world's species having reports of entanglement (Kühn and van Franeker 2020; O'Hanlon et al. 2021).

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Table 1. Summary and example publications of ingestion and entanglement in bird and mammal groups that have been reported within the Arctic region, and beyond the Arctic for comparison.

		Examples of reported plastic ingestion in the Arctic region	Examples of reported plastic ingestion outside of the Arctic	Examples of plastic entanglement reported in the Arctic region	Examples of plastic entanglement reported outside of the Arctic
Birds					
	Seabirds (auks, petrels, gulls, skua, etc.)	Robards et al. 1995; Gavrilo 2019	Young et al. 2009; Lavers et al. 2014; Le Guen et al. 2020	Bergmann et al. 2017; Gavrilo 2019	Votier et al. 2011; Costa et al. 2020
	Waterbirds (ducks, geese, cranes, etc.)	Holland et al. 2016	Gil-Delgado et al. 2017; Reynolds and Ryan 2018	Gavrilo 2019	Ryan 2018
	Shorebirds (plovers, sandpipers, etc.)		Lourenço et al. 2017		Ryan 2018
	Terrestrial birds (warblers, pipits, longspurs, etc.)		D'Souza et al. 2020		
	Birds of prey (eagles, osprey, owls, ravens, etc.)		Ballejo et al. 2021		Ryan 2018
Mammals					
	Cetaceans (whales, dolphins, and porpoises)	Moore et al. 2020	Zantis et al. 2021		Panti et al. 2019
	Pinnipeds (seals, sea lions, and walrus)	Carlsson et al. 2021	Zantis et al. 2021	Bergmann et al. 2017	Jepsen and de Bruyn 2019
	Bovids (muskox, goat, and sheep)		Omidi et al. 2012		
	Cervids (reindeer/caribou)		Chauhan 2019; Harne et al. 2019	Bergmann et al. 2017	
	Canids (wolf and fox)	Hallanger et al. 2022; Technau 2021			
	Mustelids (mink, ermine, and otter)		Santillán et al. 2020		
	Bears (polar and grizzly)	Unpublished data, referenced herein			

Globally, there is increasing attention on understanding the transfer of chemicals from ingested plastics to the tissue of mammals and birds. Some studies have found a significant correlation between ingested plastics levels and specific persistent organic pollutants (POPs) in bird tissues, in particular those with little biomagnification (Tanaka et al. 2019; Neumann et al. 2021), while others have shown findings to the contrary (Herzke et al. 2016; Provencher et al. 2018). Studies examining albatrosses and petrels outside of the Arctic have also shown a connection between ingested plastics and trace metals (Lavers and Bond 2016). Recently, more plastic additives have gained attention in relation to uptake from ingested plastic particles. Laboratory-based studies demonstrate that additive compounds can leach into stomach oil of seabirds (Kühn et al. 2020). Studies in several different ecosystems globally have also detected plastic additives in wild birds and mammals. For example, phthalates and their metabolites have been reported in fin whales (*Balaenoptera physalus* (Linnaeus, 1758)) from the Mediterranean (Fossi et al. 2012), bottlenose dolphins (*Tursiops* spp.) in the southern USA (Hart et al. 2018), in several whales in the North Atlantic (Routti et al. 2021), and in seabirds in the North Pacific (Padula et al. 2020). Organophosphate flame retardants have also been detected in fin whales from the North Atlantic (Garcia-Garin et al. 2020). A recent study also reported a correlation between plastic additives in the preen oil of several seabird species from different ocean basins and the amount of ingested plastics, while POPs were ubiquitously present (Yamashita et al. 2021).

Litter entanglement of Arctic mammals and birds

Mammals

Entanglement has been observed for several marine and terrestrial Arctic mammal species, including several whale species, harbour seals (*Phoca vitulina* Linnaeus, 1758), bearded seals (*Erignathus barbatus* (Erxleben, 1777)), as well as polar bears (*Ursus maritimus* Phipps, 1774), and reindeer/caribou (Beach et al. 1976; Bergmann et al. 2017; Nashoug 2017; Hallanger and Gabrielsen 2018; Liboiron et al. 2020). There is limited published information for several Arctic regions, and no information is currently available in the literature on spatial or temporal trends of entanglement in either terrestrial or marine Arctic mammals (Collard and Ask 2021). Because there is no coordinated effort to report and track

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mammal entanglement in the Arctic, it is difficult to evaluate the extent and development of entanglement over time.

Birds

Likewise, while there are anecdotal reports of entanglement in, or nest incorporation, of plastic, for bird species in the Arctic, there is limited published information on this topic. Although some reports exist of Arctic-breeding birds entangled in plastic material (Bergmann et al. 2017; Gavrilo 2019), most are from regions outside the Arctic, including areas visited by Arctic species through their annual migratory cycle (Ryan 2018). Similarly, nest incorporation has also been observed in the southern ranges of several seabird species that also breed in the Arctic (Hartwig et al. 2007; O'Hanlon et al. 2019). For example, in eastern Canada (south of the Arctic region), Montevecchi (1991) found that 97% of northern gannet (*Morus bassanus* (Linnaeus, 1758)) nests sampled in 1989 contained plastic debris. However, after the cod moratorium in 1992, this number decreased to 28% by 2007 (Bond et al. 2012). Moreover, northern gannets are also known to become entangled in plastic debris in nests (e.g., Votier et al. 2011). In Denmark, 57% of black-legged kittiwake (*Rissa tridactyla* (Linnaeus, 1758)) nests sampled in 2005 contained plastic debris, an increase from 39% in 1992 (Clemens and Hartwig 1993; Hartwig et al. 2007). Within the Arctic plastic has been found in the nests of Ivory gulls (*Pagophila eburnea* (Phipps, 1774)) on flat-ground colonies in the Russian high Arctic (Gavrilo 2019). These studies demonstrate that nest incorporation and entanglement can be monitored to assess spatial and temporal trends; however, there is little published information for these species in the Arctic part of their range.

Litter and microplastic ingestion by Arctic mammals and birds

Marine mammals

Compared to other animal groups, few published reports have been produced on ingested plastic in Arctic mammals, with the majority of the effort focusing on the presence of plastics in the gastrointestinal tract of individuals. One of the studies with the largest sample sizes examined 142 stomachs of seals from Hudson Bay in the Canadian Arctic for accumulated plastics. This sample included ringed seals (*Pusa hispida* (Schreber, 1775); $n = 135$), bearded seals ($n = 6$), and one harbour seal, but detected no plastic particles greater than 425 μm (Bourdages et al. 2020). All seals had been collected by Inuit harvesters between 2007 and 2019 in collaboration with research programs focused on seal diet, health, and contaminants. A similar study is underway in Nunatsiavut that explores microplastic ingestion in seals in more detail, examining the entire gastrointestinal tract and a smaller class of plastics (Pijogge and Liboiron, unpublished data). Recent work in the Greenland Sea examined hooded (*Pagophilus groenlandicus* (Erxleben, 1777); $n = 10$) and harp seals (*Cystophora cristata* (Erxleben, 1777); $n = 8$), and found macroplastics (>5 mm) in only one hooded seal pup (*C. cristata*; Pinzone et al. 2021). A new study by Mikkelsen et al. (2022) also shows that when examining seal stomachs for plastic ingestion, the portion of gastrointestinal tract may be important to consider. These studies illustrate that methods are important to consider when comparing studies reporting different types and sizes of plastic pollution.

Elsewhere, dietary studies have intermittently reported plastic debris in a variety of Arctic whale species (Fig. 1A). A narwhal (*Monodon monoceros* Linnaeus, 1758) was stranded in Belgium in 2016 with large amounts of ingested plastics (Haelters et al. 2018). Whereas in collaboration with Inuvialuit harvesters (2017 and 2018) in the western Canadian Arctic, Moore et al. (2020) found approximately 100 pieces of microplastics (20–425 μm) in the gastrointestinal tract of beluga whales (*Delphinapterus leucas* (Pallas, 1776)), assessed by chemical digestion of tissues. It is likely that the prey species of Arctic mammals play a role in the exposure of mammals to microplastics, and that feeding behaviour contributes to ingestion via trophic transfer (Lusher et al. 2016). Five important prey species for beluga whales in the Eastern Beaufort Sea (Arctic cod *Boreogadus saida* (Lepechin, 1774), saffron cod *Eleginus gracilis* (Tilesius, 1810), Arctic cisco *Coregonus autumnalis* (Pallas, 1776), four-horn sculpin *Myoxocephalus quadricornis* (Linnaeus, 1758), and capelin *Mallotus villosus* (Müller, 1776)) were evaluated for microplastics, revealing an abundance of fibres (mean: 1.42 ± 0.44/individual; Moore et al. 2022). The authors estimated that individual beluga may ingest between 3800 and 145000 microplastics annually through trophic transfer, although accumulation processes in the gut and other tissues and health implications remain uncertain.

Plastic and other debris were found in the stomachs of harvested polar bears in Alaska (25% of samples; Stimmelmayr, personal communication, 2021), and also found in the gastrointestinal tracts from polar bears in Nunavut, Canada (Provencher et al., unpublished data). Polar bear faeces full of polystyrene debris have been observer near abandoned cabins in Franz Josef Land (Gavrilo, unpublished data). A new review of polar bear ecotoxicology emphasizes how little published knowledge exists on this subject, and suggests that polar bears are unlikely to ingest considerable amounts of plastics through their prey because they mainly feed on seals (which themselves to date have shown little to no retention of plastic items), though there are too few studies on seals to validate this hypothesis across the Arctic (Routti et al. 2019). These different results on the amount of plastics accumulated in polar bear stomachs underline that more work is needed to understand how polar bears in different regions may be exposed to both macro- and microplastics. However, as the climate warms, polar bear diet may be changing (McKinney et al. 2013; Lippold et al. 2019), potentially exposing them to more plastics (and other contaminants). Indigenous harvesters in Nunavut, Canada, have reported that polar bears are frequently observed feeding from landfills and near urban sites; these may expose bears to more plastic debris (as reported in the following meetings—Arviat Hunter and Trapper Organization meeting, 2017; Resolute Bay Hunter and Trapper Association meeting, 2016). Hunters in Nunavut also report plastics and other debris items in polar bear stomachs

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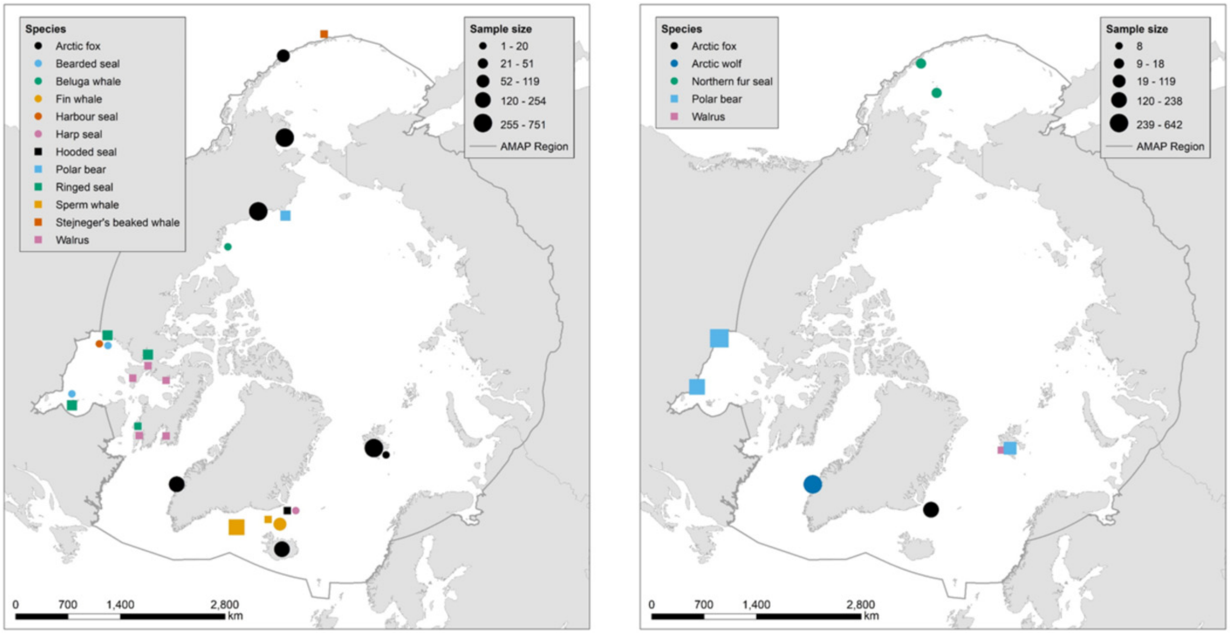
Fig. 1. (A) Mammal studies on litter and microplastics across the Arctic via the gastrointestinal tract, color-coded by species, icon size representing samples size in each study. (B) Mammal studies across the Arctic on litter and microplastics via scat analysis, color-coded by species, icon size representing samples size in each study. Base map—https://gadm.org/, North Pole Lambert Azimuthal Equal Area projection, and coordinate system: GCS WGS 1984. Data sourced from gastrointestinal tracts (Garrott et al. 1983; Martin and Clarke 1986; West 1987; Sadove and Morreale 1989; Prestrud 1992; Kapel 1999; Walker and Hanson 1999; Anthony et al. 2000; Bourdages et al. 2020; Moore et al. 2020; Pinzone et al. 2021; Technau 2021; Hallanger et al. 2022) and scat (Russell 1975; Marquard-Petersen 1998; Gormezano and Rockwell 2013; Bergmann et al. 2017; Donohue et al. 2019; Carlsson et al. 2021; Technau 2021).



and scat (as reported in Cape Dorset Hunter and Trapper Organisation meeting, 2015).

Scat samples can be used to study the exposure and uptake of litter and microplastics by Arctic marine mammals (Fig. 1B), but they have not been widely used. Historically, scat samples used for dietary analysis have reported the occurrence of plastic and "garbage" or "debris" in polar bears from Svalbard (Iversen et al. 2013) and Hudson Bay, Canada (Russell 1975; Gormezano and Rockwell 2013). The % occurrence reported in all studies appeared to be low, with 3/119 (2.5%) scats from Svalbard (2003–2021; Iversen et al. 2013) and 41/642 (6.4%) from Hudson Bay (Gormezano and Rockwell 2013). More recent exploratory research specifically targeting microplastics found that walrus (*Odobenus rosmarus* (Linnaeus, 1758)) scat samples from Svalbard showed evidence of ingestion and egestion of plastics (Carlsson et al. 2021), and a pilot program examining the scat of polar bears for microplastics is underway in northern Canada (Provencher et al., unpublished data). The presence of microplastic fibres and fragments was reported in scats of the northern fur seal (*Callorhinus ursinus* (Linnaeus, 1758)) from Alaska and California (*n* = 44; Donohue et al. 2019). Plastics monitoring by sampling scat of Arctic mammals may be a promising, non-invasive monitoring method, but several methodological issues need to be considered as samples can be contaminated with microplastics from air, water, or anthropogenic activities during collection, for example, the need to exclude fibres from calculations of microplastics in field collected scats (Carlsson et al. 2021). Like other ingestion studies, the mode of interaction cannot be readily discerned, be it by direct feeding or a consequence of secondary ingestion from consuming prey that already contains litter items (i.e., trophic transfer).

Terrestrial mammals

Little information has been published on the uptake of plastics by terrestrial Arctic mammals, although data exist on plastic ingestion by Arctic fox (*Vulpes lagopus* (Linnaeus, 1758)) and the Arctic wolf (*Canis lupus arctos* Pocock, 1935) (Fig. 1B). Plastic was listed as a dietary item along with other garbage in a study of Arctic wolf faeces (*n* = 451) from Greenland (Marquard-Petersen 1998). More recently, the stomachs and intestines of Arctic foxes (n = 20) were investigated as part of the annual fur trap in Svalbard (Hallanger et al. 2022). Parts of a "Tetra-pak" cream carton and cotton rope were found in two separate individuals. Earlier investigations also observed garbage, including plastics and paper, in 5% of the Arctic foxes examined between 1977 and 1989 in Svalbard (*n* = 751; Prestrud 1992), and 9% of fox stomachs analysed from Alaska (8/86 in 1975; West 1987). Human refuse (not defined) ranged between 0% and 4% of sampled Arctic fox individuals (*n* = 691; 1986–1991; Anthony et al. 2000). Scats have also been investigated to assess the importance of garbage in Arctic fox diet in

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Alaska. Garrott et al. (1983) found that 6% of Arctic fox scats examined contained refuse (*n* = 566, 1975–1978), but a similar investigation a few years later found no anthropogenic litter in the 193 scats from Aleutian Island, Alaska (1981–1982; West 1987). Observations of increasing frequency of occurrence of anthropogenic litter (including plastics, paper, cloth, and rope) appear to be linked to the presence of human settlements (*n* = 254; Kapel 1999). A recent study from Iceland examined plastic accumulation and egestion in Arctic foxes from 1999 to 2020 (Technau 2021). The frequency of occurrence of ingested plastic pieces for all 238 samples was 5%, and none of the samples contained more than one plastic item. These studies show how plastic ingestion and accumulation can be highly variable, even within a species at the regional scale.

Seabirds

Several groups of Arctic seabirds ingest plastic particles, but most have relatively low plastic burdens. The most studied species in the Arctic include northern fulmars (*Fulmarus glacialis* (Linnaeus, 1761)), short-tailed shearwater (*Puffinus tenuirostris* (Temminck, 1836)), black-legged kittiwakes, common eiders (*Somateria mollissima* (Linnaeus, 1758)), dovekies (or little auk; *Alle alle* (Linnaeus, 1758)), black guillemots (*Cepphus grylle* (Linnaeus, 1758)), and parakeet auklets (*Aethia psittacula* (Pallas, 1769)) (Fig. 2). The foraging strategy and prey of seabirds influence the ingestion and retention levels of litter and microplastics (Avery-Gomm et al. 2013; Poon et al. 2017; Roman et al. 2019; Baak et al. 2021). For example, Poon et al. (2017) found that accumulation rates differed among four seabird species examined in a single colony in northern Canada. They were different between groups, but similar within foraging strategies; surface feeders had higher levels of plastic in their stomachs than species that fed primarily by way of pursuit diving. Importantly, some species that can be sampled in the Arctic migrate long distances, and thus likely reflect plastic ingestion from areas beyond the Arctic. Therefore, species annual ranges influence plastic levels in seabirds, as well as the residence times of plastic particles in the gut of the bird (Robuck et al. 2022). As a result, monitoring data on plastic ingestion by seabirds cannot be combined across species into a single metric, and foraging strategies must be considered in the data interpretation. Additionally, many species were collected opportunistically, often as an "add-on" to a larger study (Baak et al. 2020*a*). While these types of samples are extremely useful for exploring patterns in ingested plastics and may align well with local wild food priorities, such opportunistic collections can lead to small sample sizes, and unbalanced sampling across regions and other biological metrics (e.g., age and sex) known to influence plastic ingestion and accumulation. As such, rigorous comparisons in trends of plastic ingestion in Arctic seabirds are challenging (Fig. 2).

Based on the plastic monitoring in northern fulmars, spatial and temporal trends have been described in many northern marine environments. For fulmars, the mass of plastic in seabirds declines with an increase in latitude, that is, individuals in the Arctic have ingested less plastic compared to sub-Arctic and temperate locations (Provencher et al. 2017; van Franeker et al. 2021). The programme of the Oslo-Paris (OSPAR) Convention for the Protection of the Marine Environment of the North-East Atlantic, which has tracked plastic pollution in the North Sea since the 1980s, has shown that the plastic levels in northern fulmars increased until about the mid-2000s and have levelled off since then in some regions (van Franeker et al. 2011; van Franeker et al. 2021). Furthermore, the levels of industrial plastics in northern fulmars (and other species) have generally declined since the 1980s when industry was engaged to alter their practices to prevent the loss of pellets to the environment (Ryan 2008; OSPAR 2009; van Franeker et al. 2011; van Franeker et al. 2021).

Even though harmonized methods exist for seabirds, studies continue to explore how other measures of ingested plastics can be used as proxies to accumulated plastics via nonlethal sampling. This is particularly important since plastic ingestion is of interest in species, where populations are declining, or may be of conservation concern. Nonlethal sampling may include sampling regurgitations from seabirds (Hammer et al. 2016), and several studies have explored the use of plastic additive concentrations in tissues like blood as a way to investigate plastic pollution ingestion levels (Hardesty et al. 2015; Tanaka et al. 2020). While nonlethal sampling is desirable, care must be taken with regard to data interpretation as results may not be comparable for different types of samples. For example, Baak et al. (2020*b*) reported no plastics greater than 1 mm in the gastrointestinal tract of thick-billed murres (*Uria lomvia* (Linnaeus, 1758)) from the Canadian Arctic, whilst the faecal precursors (i.e., guano) of the same specimens contained microplastics for 17% of the birds (Bourdages et al. 2021). This illustrates that methods of sampling and processing can lead to different results, and different measures of plastics in a bird are not necessarily correlated (Bourdages et al. 2021). More work is needed to understand how gut examination and other methods may be aligned in the future to minimise impacts on seabird populations.

Terrestrial and coastal birds

Most work assessing plastic ingestion in shorebirds has come from outside of the Arctic, although the work includes Arctic breeding species (Flemming et al. In press). Robards et al. (1997) reported plastic pollution in a single red phalarope (*Phalaropus fulicarius* (Linnaeus, 1758)) sampled in Alaska in the 1990s. Similarly, Day (1980) reported plastic pollution in two of three red-necked phalaropes (*Phalaropus lobatus* (Linnaeus, 1758)) examined in the same region of Alaska in the 1970s. Like seabirds, it is believed that foraging location influences plastic accumulation in other bird groups, and because most shorebirds feed in marine, freshwater and terrestrial environments, understanding their ecology is critical to interpreting their exposure to plastic pollution. Beyond the Arctic, more species of Arctic-breeding shorebirds have been reported to ingest plastic, and sample sizes are usually

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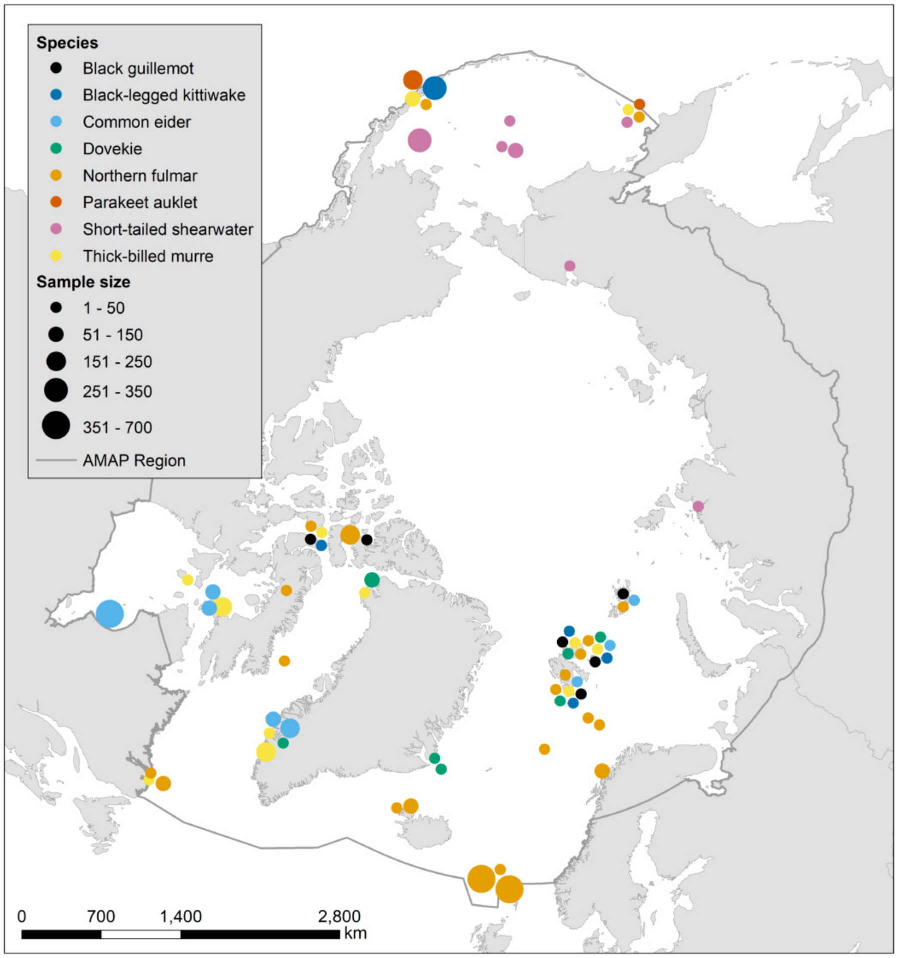
Fig. 2. Most studied species for litter and microplastics (northern fulmars (*Fulmarus glacialis*): 25 studies, thick-billed murre (*Uria lomvia*): 14 studies, short-tailed shearwater (*Ardenna tenuirostris*): 9 studies, black-legged kittiwake (*Rissa tridactyla*): 8 studies, common eider (*Somateria mollissima*): 8 studies, dovekies (*Alle alle*): 8 studies, black guillemot (*Cepphus grylle*): 6 studies, and parakeet auklet (*Aethia psittacula*): 6 studies) and where they have been sampled across the Arctic, colored by species. Sample icon represents sample size. Base map—https://gadm.org/, North Pole Lambert Azimuthal Equal Area projection, coordinate system: GCS WGS 1984, and data were sourced from Baak et al. (2020*a*).



larger. For example, black-bellied plovers (*Pluvialis squatarola* (Linnaeus, 1758)) have been sampled in other regions (i.e., Portugal and Guinea-Bissau), and found to ingest microplastics (Lourenço et al. 2017). This work highlights the need to consider Arctic-breeding animals beyond the borders of the Arctic to understand the extensive effects of plastic pollution on migratory species that use the Arctic for only part of their annual cycle.

To the best of our knowledge, no studies have been published on plastics ingestion by terrestrial birds in the Arctic, though species such as ptarmigan, grouse, snowy owls (*Bubo scandiacus* (Linnaeus, 1758)), buntings, and others forage in similar areas to foxes, reindeer/caribou, and other terrestrial animals that are known to ingest and accumulate plastics. Some of these species form an important component of the diet for many Arctic communities; therefore, this knowledge gap should be addressed to understand how these species may ingest and accumulate plastics.

Existing monitoring initiatives for litter and microplastics in mammals and birds in the Arctic

Monitoring of plastic levels and trends in mammals and birds in the Arctic

Studies on plastics in Arctic mammals have mainly focused on research into the impact of litter and microplastics on various species. One example of a mammal-focused plastic monitoring programme is the Nunatsiavut Government long-term plastic monitoring programne for ringed seals from throughout their land claim area, which is entering its third year as of 2022 (Pijogge and Liboiron 2021*b*). Ringed seal is a key species of wild food for Nunatsiavimmiut and thus a priority species for monitoring in the region. Like many other community-based monitoring programmes, results are first reviewed and analysed by the Inuit government and rightsholders, and only then reported in scientific literature, so

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these data take longer to enter the global scientific community (Pijogge and Liboiron 2021*a*).

Unlike mammals, various programs have begun to examine both effects and trends of plastic particles in birds, specifically the northern fulmar, although these are limited to only a few regions to date. Using northern fulmar as a biological indicator for establishing trends, a plastic pollution monitoring programme has been in place under OSPAR for several decades (van Franeker et al. 2021). Originally, the regional Ecological Quality Objective (EcoQO), a metric that includes plastic ingestion data for a policy framework, was based on northern fulmar data from the North Sea, but now also includes fulmar data from Iceland, the Faroe Islands, northern Norway (including Svalbard), and remote Canadian high Arctic populations (Provencher et al. 2017; van Franeker et al. 2021). Likewise, northern fulmars have been included in plastic monitoring initiatives in Greenland since 2016, with a focus on stomach analyses of birds from the west coast of Greenland. The current definition of OSPAR's marine plastics EcoQO is: "There should be fewer than 10% of northern fulmars having 0.1 g or more plastic in the stomach in samples of 50–100 beached fulmars from each of 5 different areas of the North Sea over a period of at least 5 years" (OSPAR 2009; p. 39). Northern fulmars breed along cliffs in the circum-Arctic region, and the protocols developed to track plastic pollution in the North Sea have also been applied to Arctic-breeding northern fulmars (van Franeker et al. 2011; Poon et al. 2017; Snæþórsson 2018; Snæþórsson 2019; van Franeker et al. 2021). The monitoring priorities and guidelines developed by AMAP for litter and microplastic in the Arctic have been aligned with the OSPAR procedures (AMAP 2021*b*). It is also notable that over the last few years, alongside studies in Canada under the Northern Contaminants Programme examining the effects of legacy contaminants, trends of plastics and plastic-related contaminants have been measured in fulmars (Lu et al. 2019; Baak et al. 2020*b*; Provencher et al. In review), which are the basis for more information on the effects of plastic pollution in the Arctic.

In a recent review of policies across the pan-Arctic, the OSPAR work was the only monitoring related to plastic pollution (Linnebjerg et al. 2021). More recently, Environment and Climate Change Canada has developed an indicator for plastic particles in northern fulmars under the Canadian Environmental Sustainability Indicators programme (ECCC 2021). While this work does not constitute a long-term monitoring programme, it lays the groundwork to continue focusing work on northern fulmars to track trends in plastic pollution as different actions and policies are enacted to try to reduce environmental plastic pollution levels. Given the weight of evidence towards the usefulness of stranded fulmars to monitor trends of plastic ingestion, AMAP has identified them as priority 1 indicators (Provencher et al. 2022).

Monitoring of plastic additives in mammals and birds in the Arctic

The monitoring of chemical contaminants in a variety of Arctic wildlife, including mammals and birds, has traditionally focussed on POPs (Braune et al. 2019; Rigét et al. 2019). Although an increasing number of screening and monitoring studies in the Arctic have addressed chemicals of emerging Arctic concern, some of which may be plastic additives (Vorkamp et al. 2019), a specific link to wildlife exposure to plastics has not been established for these contaminants. To date, there are no focused monitoring programmes specifically directed to monitor plastic additives (Hamilton et al. In press).

Some studies have investigated the relationship between ingested plastics and POPs present in the animals (Herzke et al. 2016; Provencher et al. 2018; Neumann et al. 2021), but very few studies have evaluated nonpersistent additive chemicals. Lu et al. (2019) examined plastic additives in northern fulmars and black-legged kittiwakes in the Canadian Arctic, based on the hypothesis that the species ingesting higher amounts of plastics (i.e., northern fulmars) would have higher levels of additives. Instead, both species of seabirds showed similar levels of chemical additives, suggesting species-specific differences in availability, absorption and (or) metabolization of the compounds, besides a possibility of more complex exposure situations. Phthalates were detected in 100% of the muscle tissues of several seabird species breeding in Alaska (Padula et al. 2020), although levels were not directly compared to ingested plastic levels across all the birds examined. Planktivorous species showed the highest levels of phthalates (Padula et al. 2020), suggesting that foraging guild influences not only the uptake of plastics, but also plastic additive accumulation in seabirds. Plastic additives have also been detected in Arctic-breeding seabird preen oil. While Provencher et al. (2020) did not detect phthalates in northern fulmar preen oil from the Canadian Arctic, a recent study showed several other plastic additives in preen oil from seabirds in Alaska and Greenland (Yamashita et al. 2021).

These differing findings highlight the need for a better understanding of links between plastic exposure and uptake of plastic additives in the Arctic and globally. Hamilton et al. (In press) underscore that chemical additives span a complex spectrum of different chemicals used for different purposes in different types of plastics which also include metals. Some are sufficiently persistent to reach the Arctic via long-range environmental transport, while others are less stable in the environment (Andrade et al. 2021). Moreover, given the central place of wild foods in the diet of Arctic peoples, a better understanding of plastics as a source of chemicals in food is necessary to assess potential impacts for human health and to align with Indigenous rights.

Benefits and challenges in the use of mammals and birds for monitoring of litter and microplastics in the Arctic

Benefits

There are several benefits to using mammals and birds to monitor litter and microplastic pollution in the Arctic environment. First, mammals and birds typically occupy the top

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of the food chain and sample large parts of the environment as they forage, thus are often used as indicators of ecosystem health (Piatt et al. 2007; Dietz et al. 2019; Velarde et al. 2019). Second, most Arctic mammals and many Arctic birds are food for human consumption (Johansen et al. 2004; Ford 2009). Because many species are actively harvested, samples can be easily obtained by collaborating with Arctic harvesters and researchers (e.g., Moore et al. 2020). For community-based monitoring programmes that target wild food, hunters would be the main and potentially only source of samples.

Seabirds usually breed in well-defined regions that are relatively easy to access for study purposes (Piatt et al. 2007) and can provide sufficient samples in a targeted sampling campaign at a single location. For the scientific community, birds have been established as useful bioindicators, with a corresponding richness of supporting data. Thus, data are available on diet (including stable isotopes to establish trophic relationships), reproduction, and contaminants in several bird species in the Arctic dating back to the 1970s (Gaston et al. 2012; Braune et al. 2014; Braune et al. 2019; Dietz et al. 2019; Foster et al. 2019; Rigét et al. 2019) and enabling co-assessments of several parameters. Plastic monitoring should be considered alongside these other studies to bring added value to existing work. This is also important when considering beached birds or those incidentally caught in fisheries (i.e., bycatch birds) which can be linked to nearby colonies or foraging areas (e.g., Colston-Nepali et al. 2020). Arctic-breeding bird species are also found outside of the Arctic, which thus provides the opportunity to establish spatial trends, provided that harmonized methods are used (Provencher et al. 2017; van Franeker et al. 2021).

While Arctic and Indigenous communities are often heralded as research assistants, these communities have their own research questions and priorities in terms of health and wild food. They can produce or co-produce science and use it to govern their foodways (ITK 2018; Pfeifer 2018; Pijogge and Liboiron 2021*b*). In the case of terrestrial mammals, local communities also have knowledge on cases of entanglement observed on their homelands. Thus, mammals and birds can serve as indicators of pollution levels and ecosystem health for international science communities but also provide information for northern peoples about their traditional diets and lands. For this reason, it is important both to collaborate with Arctic-based, Indigenous researchers to understand research priorities (ITK 2018), as well as ensure typically consumed tissues are included in monitoring by the wider scientific community. Finally, given the centrality of wild food in Arctic diets and cultures, partnering with northern communities to understand how to best report science around wild food is an ethical imperative of such work (Pijogge 2017; Pijogge and Liboiron 2021*a*).

Challenges

One obvious logistical challenge for many mammal monitoring programmes is the sheer size of some of the individuals and their organs to be examined for litter and microplastics. For example, polar bears can weigh 400 kg, a narwhal can weigh 900 kg, and a walrus weighs 1000 kg; all of these require extra equipment (e.g., powered vehicles) to move. Second, with such large and cumbersome samples, it may be difficult to minimize the chance of contamination, especially by ubiquitous microfibres (e.g., Moore et al. 2020). Third, for some groups such as whales, sample numbers are necessarily small because of conservation measures (e.g., imposed harvest limits); potentially affecting the statistical power of trend analyses. For both mammals and birds, there are regions where a large number of individuals cannot be sampled for plastic monitoring through local harvests, due to the distribution of Arctic communities, wildlife aggregation sites, or protection measures. For example, in Greenland, Canada, and Alaska, limited numbers of polar bears are regularly harvested or sampled for contaminants (Fig. 1), but in other Arctic regions, polar bear samples would be extremely restricted. Similarly, in the Faroe Islands, the pilot whale (*Globicephala melas* (Traill, 1809)) and Atlantic white-sided dolphin (*Lagenorhynchus acutus* (Gray, 1828)) harvest could be used to access samples to study plastic ingestion regionally, but these species are not harvested in large numbers in other regions, limiting comparisons on spatial trends.

There are also several limitations for using seabirds as an indicator of environmental plastic pollution in the Arctic. First, most past studies are limited to plastic and debris that are greater than 1 mm; therefore, their current use to study smaller microplastics is limited. For both mammals and seabirds, some studies have included smaller size classes of microplastics, but these findings may reflect local environmental levels more easily sampled via other compartments such as sediments or invertebrates (Grøsvik et al. In press; Martin et al. In review). In terms of monitoring, only species that can be reliably sampled in regions where they regularly breed, are harvested, or where carcasses wash ashore, can be used to track trends spatially or over time. Lastly, both mammals and seabirds can be long-lived and migrate over long distances. This implies that their route and rate of egestion of plastics need to be known to understand the rates of accumulation and exactly what their accumulated plastic pollution reflects, which is better understood currently in birds given their return to known foraging ranges around their breeding colonies (Ryan 2015; van Franeker and Law 2015). Mammals and birds are not evenly distributed across the Arctic, and therefore there will be geographical gaps in monitoring programs that aim to examine litter and microplastics via seabirds. For example, the western part of the Canadian Arctic Archipelago and the central Russian Arctic have limited numbers of cliff-nesting seabirds, the main type of seabirds used for contaminants monitoring in the Arctic (Fig. 2). When seabirds are being monitored as part of local food webs this regional limitation is less of a concern, since the goal of food web monitoring is to evaluate the amount of plastics in human food rather than as indicators of wider environmental levels.

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Recommendations for future monitoring and research efforts

Shared priority setting in litter and microplastic monitoring in the Arctic

An important consideration in creating future monitoring and research efforts is how the priorities and insights of an international scientific community do not necessarily align with the research needs and priorities of Indigenous peoples in the Arctic (ITK 2018; Pfeifer 2018). For example, existing research has shown that some of the methods, categories, and research questions in studying plastic pollution in the Arctic are skewed towards southern understandings and landscapes (Liboiron et al. 2021; Melvin et al. 2021). The Inuit Tapiriit Kanatami, an organization representing over 65 000 Inuit in Canada, states that, "for far too long, researchers have enjoyed great privilege as they have passed through our communities and homeland, using public or academic funding to answer their own questions about our environment, wildlife, and people. Many of these same researchers then ignore Inuit in creating the outcomes of their work for the advancement of their careers, their research institutions, or their governments. This type of exploitative relationship must end" (ITK 2018, p. 3). Given the intersection of Arctic mammals, birds, and Indigenous food sovereignty, some of the recommendations from Inuit Tapiriit Kanatami's *Northern Inuit Strategy on Research* are relevant to future monitoring of plastics in the Arctic, including advancing Inuit governance in research, being part of funding decisions; enhancing the ethical conduct of research, including strong community partnerships; ensuring Inuit access, ownership, and control over data and information gathered in their homelands, and building capacity in Inuit research through skill-sharing, equal partnership, and research infrastructure (ITK 2018, p. 4). This exceeds simply sampling species used for food or including Inuit and other Arctic peoples in sample collection. While each Indigenous group and community in the Arctic will be different, many of these principles will hold across the Arctic and should be considered in all future monitoring and research efforts.

Monitoring of physical litter and microplastics across global marine ecosystems

For the international scientific community, monitoring that can identify shifts in abundance and types of plastics across multiple sites in the Arctic is crucial. This type of information is also needed by risk assessors and policy-makers. Given the accumulation of plastic particles in fulmars, the use of fulmars to track plastic pollution in several regions, and their wide distribution in the Arctic region, fulmars are a primary candidate for monitoring of plastic pollution in the Arctic. We recommend that where possible and relevant, immediate monitoring of ingested plastics in northern fulmars be implemented. Sample sizes will depend on local populations, and access to samples will be possible via fisheries bycatch, harvest, or via local efforts (e.g., beached bird surveys). In regions where fulmars are less available, an alternative species with similar foraging habitats that has also been studied in the Arctic is the short-tailed shearwater (Fig. 2; although this species breeds outside the Arctic and must be considered as an Arctic indicator within this context). Future studies should consider this group of procellarids together, and how their plastic burdens may be comparable to consider patterns across a wider region of the Arctic (e.g., comparisons between the western and eastern Arctic regions). Future work should also consider adding polymer identification to monitoring programmes to better monitor potential changes in polymer types and provide data on chemical contaminants in relation to plastic pollution.

While the northern fulmar represents an important indicator for tracking plastics in the environment, most Arctic seabird species have relatively low levels of plastic ingestion. For example, thick-billed murres and common eiders are two commonly harvested seabirds in the Arctic, and have very low levels of plastic ingestion (0%–3%; Baak et al. 2020*b*; 9%–10%; Liboiron et al. 2020). In contrast, few fulmars and kittiwakes are harvested in most Arctic countries, but these species have a higher frequency of occurrence of plastics (Baak et al. 2020*a*). Given that foraging ecology and prey type appear to greatly influence whether seabirds accumulate plastics in their stomachs, we recommend that it is important to monitor a variety of seabird species with different foraging ecologies (e.g., surface-feeders vs. pursuit divers; surface, pelagic zone, and benthos feeding), as all may provide different exposure levels to different types of plastic (Baak et al. 2020*a*) or chemical additives. Thus, Arctic seabird monitoring programmes focused on plastic pollution should consider the inclusion of the widely distributed northern fulmars, black-legged kittiwakes, thick-billed murres and common eiders as species that will track plastic pollution across several areas of the marine ecosystem (Baak et al. 2021).

Currently, there is a lack of global monitoring and baseline data for mammals, making them a less ideal tool for indicating large-scale changes in plastic pollution. Yet, research should continue to explore the plastic retention patterns in mammals, particularly when they are part of local food webs. In time, monitoring for physical plastic pollution may become more important in mammals at the pan-Arctic scale for the scientific community and policy-makers, yet more work is needed before levels, trends, and variation in ingestion levels by region and species can be assessed.

Developing tools to monitor plastic pollution in terrestrial environments

Compared to the marine environment, very little is published about litter and microplastics in the Arctic terrestrial environment, including terrestrial mammals and birds. However, like the marine environment, many terrestrial species are harvested in the North (geese, reindeer/caribou, and foxes), and collaborative research programmes with communities are a potential avenue for meaningful research and developing tools for monitoring. For example, Arctic foxes can be considered for microplastic and litter monitoring in regions where fox populations interact with human settlements (Technau 2021). Collection and analyses of scat can also be used to assess ingestion of litter and microplastics,

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and is not lethal so individuals in a region can be tracked over time (Technau 2021). Scat collections are a less invasive study method, which is beneficial, although examination of microfibers is limited in scat samples because of the potential for airborne contamination. Arctic foxes are hunted during winter in several regions for their fur, which could provide samples for litter and microplastic analyses (Technau 2021). Additionally, because there are efforts to track and harvest foxes for disease studies and fur (Collard and Ask 2021; Nadin-Davis et al. 2021), litter and microplastics sampling could be added to these existing programmes with few additional resources.

Future work on plastic pollution should also focus on terrestrial species that are commonly consumed by northern communities. While microplastic ingestion and plastic additives in tissues of species such as reindeer/caribou, hares, and other species that forage and live in the terrestrial environment are unpublished to date, future work should consider how these species may be exposed to plastic pollution, and its effects. Several bird species may also be useful for tracking plastic pollution in the terrestrial environment, notably waterfowl (Holland et al. 2016), but currently very little is published about how bird species that use the terrestrial environment interact with plastics in the Arctic, either via ingestion or entanglement. In southern habitats, swallows have been examined as potential indicators of microplastics (Sherlock et al. 2021), but results suggest that like many other groups, site and sample type influence the findings, and further research is needed to understand how birds in the terrestrial environment may be exposed to plastic pollution.

Source and surveillance monitoring

In many regions of the Arctic, shoreline surveys have illustrated that derelict fishing gear is a large component of litter in the marine environment (e.g., Alaska, Barents Sea region) (PAME 2019). How mammals and birds may become entangled in this type of litter in the Arctic is understudied and may be an important consideration for the impacts of large plastic litter. In some areas there are coordinated efforts to track how animals are entangled (e.g., via stranding networks). Future monitoring for litter should consider coordinating such reporting in the Arctic, for example through existing platforms such as SIKU, “a mobile app and web platform by and for Inuit” focused on sharing observations while on the land (siku.org). For any programs that contribute to source and surveillance monitoring, reporting should include information on the animals, and the litter involved. This can be achieved through reporting categories that are similar to shoreline surveys in the region, which would allow these types of data to be compared and contrasted.

Similarly, several bird species may be useful indicators in relation to waste management in some regions. Gulls and corvids are known to frequent sites where waste is accessible, and may ingest plastic particles, which can be tracked through examination of regurgitated pellets (boluses) (Baak et al. 2021). Given that gull boluses are regurgitated regularly, these pellets reflect local sources of plastic pollution. When bolus examination is paired with polymer identification or brand audit, bolus examination can directly inform where litter is escaping into the environment near gull colonies (Ballejo et al. 2021). Several species are known to use plastic pieces to build nests. Nest incorporation and entanglement have been observed in several Arctic-breeding seabird species, such as northern gannets, black-legged kittiwakes and ivory gulls (e.g., Hartwig et al. 2007; Votier et al. 2011; O’Hanlon et al. 2019; O’Hanlon et al. 2021). Recent studies are also reporting litter in the nests of common eiders, Atlantic puffin, black-legged kittiwakes and glaucous gulls (*Larus hyperboreus* Gunnerus, 1767) in Svalbard (Gabrielsen, unpublished data), and in great cormorant (*Phalacrocorax carbo* (Linnaeus, 1758)), European shag (*Phalacrocorax aristotelis* (Linnaeus, 1761)), northern gannet, common eider, kittiwake, ivory gull, herring gull (*Larus argentatus* Pontoppidan, 1763), glaucous gulls, Heuglin’s gull (*Larus heuglini* Bree, 1876) and Vega gull (*Larus vegae* Palmen, 1887) in Russia (Gavrilo, unpublished data). These emerging studies will be critical to understanding how widespread nest incorporation is in the Arctic. Importantly, because the use of plastic debris as nesting material is associated with the abundance and availability of plastic debris in the local marine environment (Bond et al. 2012), monitoring the use of plastic pollution in nests can also provide information on the amount and type of plastic pollution in the local marine environment. Thus, we suggest that nest incorporation and entanglement of plastic debris are monitored at bird breeding colonies in relation to local and regional plastic pollution reduction strategies.

Future additives monitoring in mammals and birds

While plastic additives are not as well studied as physical litter and microplastics, there is a growing body of knowledge on additives in Arctic wildlife. As outlined above, plastic additives have been detected in seabird liver, eggs and preen oil, as well as in seal liver (Lu et al. 2019; Padula et al. 2020; Yamashita et al. 2021). Importantly, as the UV stabilizer UV-328 is now being considered under the Stockholm Convention (i.e., international regulation to eliminate or restrict the production or use of certain POPs), there is a need to better understand its transport, distribution and fate in the environment, including the Arctic (Stockholm Convention 2021).

Both marine mammals and seabirds should be considered for plastic additive monitoring based on the existing contaminant programmes in the Arctic (Rigét et al. 2019). Tissues that are regularly sampled in marine mammals and seabirds (e.g., seal liver and seabird eggs) should be targeted, at least initially, to screen Arctic species for plastic additives (e.g., Lu et al. 2019). Tissues regularly consumed by humans should also be selected to provide information on human exposure to plastic additives via the consumption of wild foods. If archived specimens are available, contemporary sampling paired with archival sampling could be used to study temporal developments in concentrations of plastic additives in biota, provided that sample storage was suitable for this purpose. Retrospective analyses have been carried out for several chemical contaminants to reconstruct time trends (Vorkamp et al. 2011; Braune et al. 2016). Further studies may also ex-

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amine plastic additives in a variety of tissues to explore in which tissues these chemicals may accumulate.

As discussed by Hamilton et al. (In press), plastic additives are a complex mixture of compounds, thus monitoring programmes need to consider what additives should be prioritized. There has been very limited work to date to consider the patterns of plastic additives in Arctic biota, and how they may change over time, across species, and differ between regions. Consideration of plastic additives in Arctic biota, and a coordinated approach to monitoring (similar to the work that has been done for litter and microplastics and contaminants for the pan-Arctic, as outlined in Provencher et al. (2022) and Rigét et al. (2019)), is needed for plastic additives, the other component of plastic pollution.

Future effects monitoring in mammals and birds

Effects monitoring is a critical component for understanding the impacts of plastic pollution in the environment, especially given the biodiversity crisis and combined impacts of climate change. Monitoring effects of entanglement is recommended as a component of source and surveillance monitoring, in particular targeting derelict fishing gear. Given the important and prominence of mammals and birds in the diets of many communities across the Arctic, effects monitoring should also address potentially more subtle effects of plastic uptake and focus on species that are: (a) consumed and (b) experience high levels of plastic accumulation. Selection of species should consider plastic pollution burdens, and plastic additives, in the context of species, populations, conservation status, and importance to local communities at the regional level. Both effects at the individual and population level are important to consider, and species should be selected where effects monitoring can include both of these levels. It is important to consider that species that do not show high levels of accumulation of physical plastic particles can still be exposed to plastic additives (e.g., seals in northern Canada; Lu et al. 2019; Bourdages et al. 2020). Candidate species for physical and chemical effects monitoring should include northern fulmars (due to the known high levels of plastic burdens). Seals, eiders, and murres should be included in programs assessing the effects from plastics related contaminants due to their importance as a food source for communities. Mammals, such as pinnipeds, should be the focus of programs aimed at understanding the effects entanglement in plastics.

The translocation of small microplastics and nanoplastics into the tissues of biota is of growing concern, and may lead to serious effects in biota (Zhang and Xu 2020; Thomas et al. 2021). The detection of these types of plastic particles remains a technological challenge, and more research is needed to evaluate the presence of these particles outside the gastrointestinal tract, and the associated effects these particles may have on biota. The effects of these smaller plastic sizes will be a critical aspect of future monitoring efforts, and should be included in monitoring programmes in addition to the detection and quantification of plastics in the gut and other tissues of the animals.

Conclusions

Monitoring of litter and microplastics in the pan-Arctic requires a multimatrix approach, which can build on existing monitoring programmes and modify methods accordingly. The currently available knowledge investigating the interactions between birds and mammals with litter and microplastics has been mostly driven by opportunistic collections, and not specifically for monitoring purposes. While using mammals and seabirds to monitor litter and microplastics requires much larger sample sizes than typically collected for consumption, or for other research programmes, the benefit is that hunter-collected and bycatch samples can inform studies on plastics and plastic additives in relation to species regularly consumed by humans. Given the current state of knowledge, a primary recommendation is that northern fulmars should be used to monitor litter and microplastics where possible to contribute to pan-Arctic spatial and temporal trend analysis and to link to monitoring outside the Arctic. Other species (e.g., black-legged kittiwakes, thick-billed murres, and common eiders) should also be considered for monitoring to better inform questions relating to plastic pollution in food webs and trophic transfer. Research on detecting litter and microplastics in mammals is still developing although pinniped and polar bear scat look promising for food web monitoring targeting bigger plastics. Currently available information is limited and should be extended prior to tracking litter and microplastics at the pan-Arctic scale. However, studies on mammals are important for addressing questions related to regional food security and safety. Local or regional efforts are not being discouraged; rather, further research is required to considering scaling to the pan-Arctic. Indeed, local and Indigenous researchers and community representatives should be part of decision-making processes for priority species and research questions in their areas. The ethics of reporting back and publishing contamination results for wild food, even if the results are null or low, is an area of crucial importance and should play a central role in monitoring projects moving forward. Lastly, seabird and marine mammal tissues should also be considered for monitoring of plastic additives and nanoplastic burdens, coupled with existing contaminant monitoring programmes, to better understand the extensive effects from litter and microplastics.

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