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The State of Marine Microplastic Pollution in the Arctic

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The Norwegian Polar Institute is Norway's central governmental institution for management-related research, mapping and environmental monitoring in the Arctic and the Antarctic. The Institute advises Norwegian authorities on matters concerning polar environmental management and is the official environmental management body for Norway's Antarctic territorial claims.
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Table of Contents

English summary

The problem of global plastic pollution is one of the most visible, and well documented, environmental changes of recent decades. The Arctic region is opening up to increasing commercial activity as sea ice melts, and will become increasingly influenced due to the detrimental effects caused by the trillions of pieces of plastic floating in our world's oceans today.

Microplastics (< five mm in diameter) can flow directly to the environment undisturbed by waste water treatment plants from applications in cosmetics, for example, or can result from eventual fragmentation of larger plastics. By nature of their small size and ubiquitous presence across different ecosystems, microplastics are available for ingestion by all trophic levels, thus the potential for detrimental effects is substantial. Plastics can transport invasive species and pollutants over long distances, both of which could act as further stressors in the Arctic under climate warming scenarios. Plastic ingestion can disrupt functions of invertebrates, and can transfer a chemical burden to organisms. Population effects of plastic ingestion are largely unknown.

Here we collate and summarise accounts of microplastic pollution in the Arctic. Very little information exists about microplastic pollution in the Arctic. This review found no records for surface trawls in the Arctic, sediment microplastic loads or coastal shore pollution. The only quantitative records that exist are biological records and sea ice records. Microplastic encounters by Arctic animals exist for seven species, of which four are seabirds, two cetaceans and one shark species. From comparative studies with northern fulmars, plastic pollution levels in the European Arctic are higher than expected when compared to lower latitudes, most likely because of water currents. Levels of plastic in sea ice are higher than in the most polluted of oceanic gyres (38 to 234 pieces per m$^{3)}$, and warn of a legacy of plastic that will be released as sea ice melts.

The many gaps in our knowledge of microplastic pollution in the Arctic require further studies. Nevertheless, a lack of information in the region should not be considered as a lack of a problem, and should not hold back any action intending to reduce marine litter in the region.

Norwegian summary/Norsk sammendrag

Den globale plastforurensning er en av de mest synlige og veldokumenterte miljøforandringer de siste 20-30 år. Som et resultat av at havisen smelter åpnes nå de arktiske områder for økt kommersiell aktivitet. Plastforurensning fra sør samt en en økt fiskeri- og skipsaktivitet i nordlige havområder har resultert i økt plastforurensning i europeisk Arktis. Denne forurensning ville kunne forårsake skadelige effekter på naturmiljøet ved at plast brytes ned til milliarder av små plastbiter (mikroplast).

Mikroplast (mindre enn 5 mm i diameter) flyter i dag direkte til naturmiljøet uten at den blir tatt opp i renseanlegg. Disse plastbitene kan komme fra produkter som for eksempel kosmetikk og vaske-midler eller være fragmenter av større plastbiter. Pga. av plastens størrelse og tilstedeværelse i miljøet kan de bli tatt opp av mange ulike organismer og dermed kunne forårsake skadelige effekter på økosystemer. Plast som driver i havet kan også transportere fremmede arter og plast tar også opp miljøgifter som medvirker til forurensning over lange avstander. Mikroplast kan være en ekstra stressfaktor for dyr i Arktis som er utsatt for klimaendringer. Inntak av plast kan forstyrre fordøyelsen til plankton, fisk og sjøfugl og kan overføre kjemiske stoffer til dyr som spiser disse organismene. Populasjonseffekter av plastforurensning er ikke påvist så langt.

Det finnes i dag lite informasjon om forurensning fra mikroplast i Arktis. I denne rapporten, som er en litteraturgjennomgang av kunnskap fra Arktis, har det ikke vært mulig å dokumentere opplysninger om mikroplast i overflatevann, i sedimenter eller i fjæresonen. De eneste kvantifiserbare opplysninger i vitenskapelig litteratur finnes for havis og studier av dyr. Mikroplast i arktiske dyr er beskrevet for syv arter; fire sjøfuglarter, to pattedyrarter og en haiart. I et komparativt studium av havhester, er plastforurensningen i europeisk Arktis høyere enn forventet når en sammenligner med lavere breddegrader. Dette er trolig et resultat av hvordan havstrømmene beveger seg. Nivå av plast i havis er høyere enn de mest forurensede hvirvelstrømmene (gyrer) i verdenshavene (38 til 234 biter per m^3). Denne plasten vil frigjøres når havisen i polområdet smelter.

Rapporten peker på flere kunnskapshull knyttet til forurensning av mikroplast i Arktis. Mangelen på informasjon fra dette området er åpenbar, og studier viser at mikroplast er et problem. Dette betyr at nasjonale og internasjonale tiltak må iverksettes for å redusere plastforurensningen i Arktis.

The problem: global plastic pollution

The global issue of marine plastic pollution is one of the most visible, and most reported, environmental changes facing our oceans at present. Plastic production has hardly ceased to increase since the onset of mass production in the 1950s, reaching 299 million tonnes worldwide in 2013 (PlasticsEurope 2015). The same qualities that led to extensive production of plastic have led to the persistence of plastic products in the marine environment well beyond their lifetime as consumer items. A durable product with exhaustive degradation times, and yet plastic is inexpensive enough to be treated as a 'throw-away' item. Indeed, half of all plastic products made are disposable, and yet require 7-8 percent of world oil and gas supply in raw products and energy for production (Hopewell et al. 2009). Our use of plastic products is unsustainable (Hopewell et al. 2009), and plastic pollution is now ubiquitous within the marine environment (Barnes et al. 2009).

Approximately 12.7 million tonnes of plastic litter enter the ocean each year (Jambeck et al. 2015) and latest estimates suggest that at least 5 trillion pieces of plastic are floating at the ocean surface worldwide (Eriksen et al. 2014). The first report of plastic pollution of the natural world came as early as the 1960s (Kenyon and Kridler 1969) when plastic production was just a fraction of what it is today (PlasticsEurope 2015). Nowadays, new reports of plastic pollution in increasingly remote environments are frequent, and the Arctic is no exception (Trevail et al. 2015).

In the Arctic, rapid environmental change will increase the vulnerability of the region to plastic pollution (Trevail et al. 2015). High biodiversity in the region will be at threat from increases in commercial activity facilitated by reductions in sea ice extent (Humphries and Huettmann 2014). It is imperative to understand current pollution levels in the Arctic in order to protect the region in the future (Brigham 2011).

This review aims to collate and summarize quantitative information about current levels of plastic pollution in the Arctic, with an emphasis on microplastics.

The Arctic, defined

The Arctic can be defined in multiple ways: the Arctic Circle delineated by 66˚ 33' 45.7" N, the 10˚C isotherm and the tree line. In light of present climate warming, and therefore the potential for the 10˚C isotherm and tree line to shift over the coming decades, this review will focus on the area within the Arctic Circle above 66˚ 34' N. Reference, however, will be made to sub-Arctic areas, which may fall within alternative definitions of the Arctic or indicate susceptibility of Arctic ecosystems or species to the effects of plastic litter.

Figure 1: The Arctic, showing the three different definitions of the region: The Arctic circle around 66˚ 34' N, the 10˚C Isotherm (red) and the tree line (dark green). Blue arrows show the two main flows of water into the Arctic as per Zarfl and Matthies (2010). Map modified from the National Snow and Ice Data Centre [Available at: https://nsidc.org/cryosphere/arctic-meteorology/arctic.html].

Microplastics; and sources to the marine environment

Pollution of the marine environment by microplastics has been the subject of increasing attention during the recent decades. Microplastics are typically defined as particles less than five millimetres in diameter (Barnes et al. 2009), although classification can sometimes vary. Sources of microplastics in the marine environment can be divided into two categories: primary and secondary pollution sources (Cole et al. 2011). When microplastics are the 'original product', and enter the marine environment after use, it is known as primary pollution. Fragmentation of macroplastics into microplastics once in the environment is known as secondary pollution. Further details, and examples, are given below.

Primary microplastic pollution

Common applications of micro-plastics are numerous. In the cosmetic industry, both toothpaste and exfoliating washes use plastic beads in place of traditional, natural ingredients (Fendall and Sewell 2009). Industrial air-blast cleaning, for example cleaning old paint and rust off engines and boat hulls, uses micro-plastics (Browne et al. 2007). In medicine, micro-plastics are used to facilitate drug delivery to delicate body organs, such as for treating brain diseases (Patel et al. 2009). After a single use, the majority of such plastics will not be taken up by the waste-water treatment plants and will therefore enter the marine environment (Browne et al. 2007; Fendall and Sewell 2009).

Industrial plastic resin pellets, typically between 2-5mm diameter, can also be classed as micro-plastics. These pellets are the raw material subsequently made into consumer items, and can be transported to the ocean via accidental losses during transport and manufacture (Cole et al. 2011).

Secondary microplastic pollution

Aside from inputs of the above 'primary' microplastics, eventual fragmentation of larger debris results in microplastics (Ryan et al. 2009). Inevitable for all plastic litter are processes such as exposure to UV radiation and wave action that will degrade the structural integrity of the plastic, leading to fragmentation. Therefore when considering microplastic pollution, evidence of macro-plastic pollution will indicate eventual presence of microplastics.

Sources of macro-litter to the environment are numerous. Marine litter can be accidental, however generally is a consequence of irresponsible human behaviour and improper waste disposal. Coastal countries alone generate 275 million tonnes of plastic waste collectively per year (Jambeck et al. 2015). Although targets exist to increase plastic recycling (PlasticsEurope 2015), citizen participation and industrial capacity are often limiting factors (Barnes et al. 2009). If not correctly managed, plastic litter can still be transported to the marine environment once disposed of. For example, sheet-type plastics are susceptible to escaping containment as are easily blown by wind (Barnes et al. 2009).

An estimated 80% of all plastic litter in the marine environment originates from terrestrial systems (Andrady 2011). Riverine inputs are considerable, for example from just two rivers in America an estimated 2 billion pieces of microplastic enter the marine environment every three days (Moore 2008). Also notable is the additional input resulting from storms, flooding and freak weather events such as tsunamis (Moore et al. 2002; Lattin et al. 2004), the magnitude of which is likely to increase with an ever more unpredictable and extreme climate (Easterling et al. 2000).

The remaining 20% of marine litter has its sources in marine activities, such as coastal tourism and recreation, marine industry (shipping, oil and gas, aquaculture etc.) and commercial fishing (Cole et al. 2011). Discarded litter or accidentally lost fishing nets, for example, will all gradually fragment into microplastics.

Quantifying microplastic abundance

Various methods have been developed to quantify plastics in the marine environment, including oceanic trawls, biological sampling, beach surveys, marine litter observations, sediment sampling and sea ice cores.

Oceanic trawls, typically using zooplankton nets or water samples, can be used to detect microplastics within the water column or surface ocean (Hidalgo-ruz et al. 2012). Provided that sufficient transects and repeats are carried out to account for natural ocean heterogeneity, a valuable map of spatial and temporal variability in oceanic plastic litter can be determined (Ryan et al. 2009). Mesh size is typically 330µm, however can vary between studies causing substantial differences in results (Cole et al. 2011). This method has been used to map plastic litter abundance on ocean-basin scales, including the major oceanic gyres (Law et al. 2010; Eriksen et al. 2013; Cozar et al. 2014), and has facilitated an understanding of the magnitude of the marine litter problem (Eriksen et al. 2014).

Biological sampling quantifies ingestion of plastic by marine animals typically by dissection. A variety of marine taxa can mistake plastic items for natural prey, and residence times of plastic in stomachs are such that they can provide a useful tool for monitoring of marine litter (Van Franeker et al. 2011; Trevail et al. 2015). The northern fulmar (*Fulmarus glacialis*) is one such species that regularly ingests plastic, and its widespread distribution across the North Atlantic, Pacific and Arctic Oceans has led not only to extensive use of the species for monitoring plastic pollution, but also the adoption of ingestion amounts into international legislation aiming to reduce marine litter (OSPAR 2008). Typically, results from biological monitoring are not separated into size classes of plastic particles, but results do include microplastics. Biological sampling led to the first accounts of plastic pollution in the marine environment that had been ingested by Laysan albatross, *Phoebastria immutabilis,* in the 1960s (Kenyon and Kridler 1969).

Beach combing for plastic litter is a straight-forward technique that can be conducted on a regular basis to assess plastic accumulation over time (Ryan et al. 2009). Although some small pieces and industrial resin pellets will be collected, this method is best suited to macroplastics. Further limitations exist in Arctic regions, where beaches are much more inaccessible and regular monthly surveys are thus unachievable.

Marine litter observations comprise of records collected by boat crews, cameras on remotely operated vehicles or by divers on the presence and type of marine debris. Again, whilst effective at surveying macroplastic debris, microplastics will rarely be accounted for. For example, at the Arctic deep sea observation station: HAUSGARTEN, near Svalbard (79˚N) an increase in marine litter was observed at the sea floor over the survey period, however the smallest size category recorded was items less than 10cm (Zarfl and Matthies 2010).

Sediment sampling can extract plastic particles from beach, estuary or seafloor sediment, typically by mixing the sediment with high-density saline water to allow low-density plastic pieces to float out of the sediment mix (Andrady 2011), or using an elutriation device (Zhu 2015). Fluorescent spectroscopy is used to identify plastic pieces.

Sea ice cores can be melted and filtered in order to extract plastic pieces, and quantify plastic concentration in sea ice. This method has only been used in one study (Obbard et al. 2014) and would benefit from further validation. As with sediment samples, plastic pieces are identified using fluorescent spectroscopy.

Microplastics in the Arctic

Relatively little is known about the state of microplastics in the Arctic in comparison to other major ocean basins. A recent review examined a total of 292 publications reporting encounters between marine debris and organisms worldwide, of which only five were from the Arctic (Gall and Thompson 2015). Similarly, a recent study evaluating microplastic pollution worldwide evaluated 101 papers including only one in the Arctic (Ivar do Sul and Costa 2014). Important to note, considering this, is that a lack of reporting does not necessarily imply a lack of impact (Gall and Thompson 2015).

(a) Oceanic/water column records of microplastics in the Arctic

This review found no records for surface or water column concentrations of microplastic litter in the Arctic: a major gap in our knowledge of global plastic litter distribution and abundance. We therefore consider here the potential for oceanic microplastic pollution in the Arctic.

Plastic can be transported huge distances with ocean currents, resulting in the spread of plastic pollution from source areas (high density of commercial marine activity and coastal towns and industries) to more remote regions, such as the poles (Barnes et al. 2009). The three major routes of water flow into the Arctic (in order of magnitude) are via the West Spitsbergen current, which originates in the North Atlantic and flows north through the Fram Strait, via the Bering Strait, which originates in the North Pacific and Bering Sea, and to the east of Svalbard into the Barents Sea (Figure 1) (Zarfl and Matthies 2010). Therefore, when considering potential levels of plastic pollution in the Arctic it is important to note oceanic levels of plastic pollution in the North Atlantic and Bering Sea.

In the North Atlantic, latest surveys found an average of 2.64 pieces of plastic per m^3 of ocean surface (Lusher et al. 2014). This is approximately 100 times lower than levels in the NE Pacific, off the coast of British Columbia, Canada, where surveys reported an average of 279 pieces per m^3 (Desforges et al. 2014). Further north, in the Southeast Bering Sea, there are on average 0.017 – 0.072 pieces of plastic per m^3 (Doyle et al. 2011). Together, currents from these water bodies may be responsible for transport of up to 16.200 to 1.9 million tons of plastic to the Arctic Ocean each year (Zarfl and Matthies 2010). Large variation in the estimated value is a result of spatial heterogeneity and temporal variability of plastic litter at the ocean surface and differing sample methods across studies.

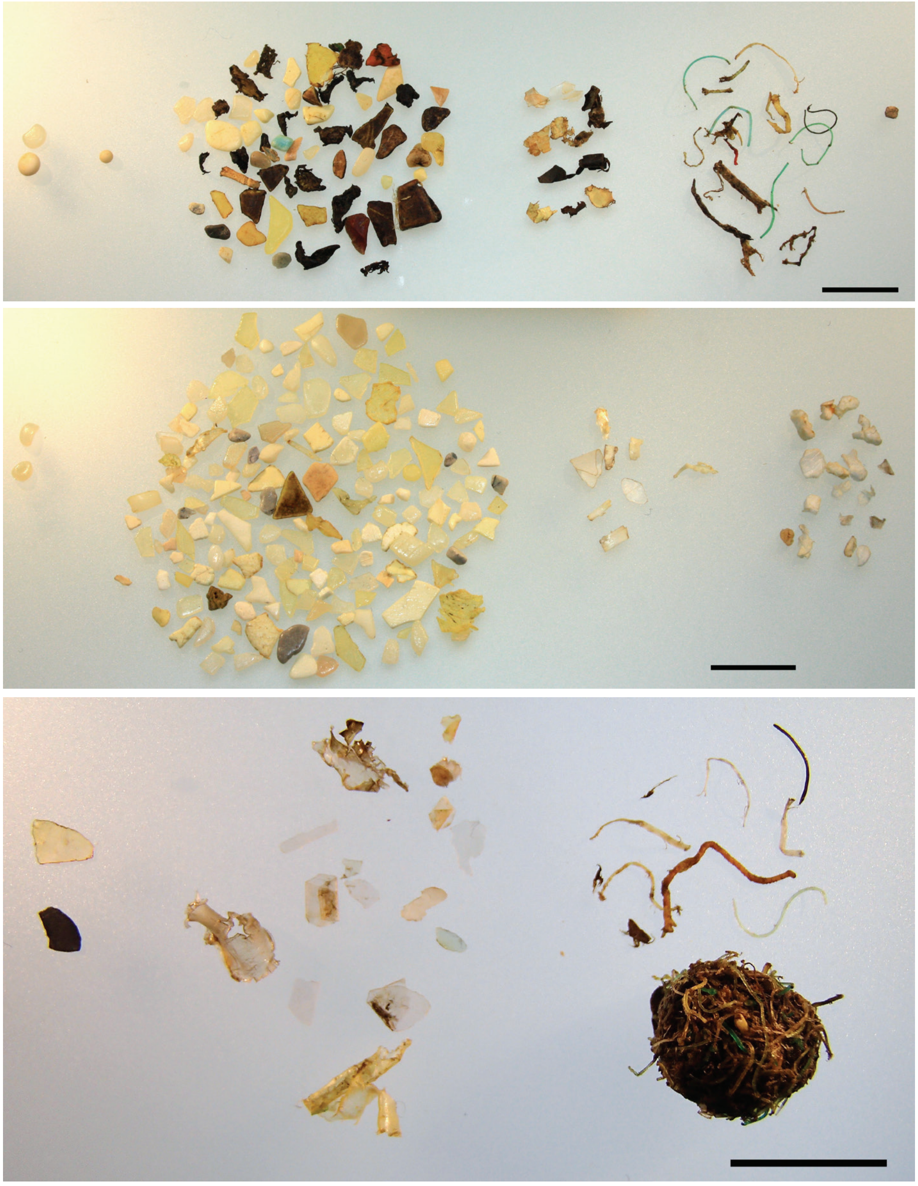
A study following surface buoy trajectories hypothesised that there is a sixth gyre within the Arctic, in the Barents Sea (Van Sebille et al. 2012). If so, microplastics would accumulate in the region because of converging ocean currents, as is the case in the five other major ocean basin gyres in the Atlantic, Pacific and Indian Oceans (Law et al. 2010). Indeed, plastic ingestion by fulmars was higher in Svalbard than expected, quite possibly as a result of ocean currents (Trevail et al. 2015). The hypothesis that an additional oceanic gyre exists in the Barents Sea would benefit from studies directed at plastic concentrations in the region.

Riverine inputs from Arctic nations could be an additional source of ocean microplastic pollution to the Arctic Ocean. For example, the Ob and Yenisei rivers in Russia, which contribute 37% of freshwater input to the Arctic, are a major source of persistent organic pollutants to the Arctic Ocean (Carroll et al. 2008). Quantities of microplastics in Arctic rivers are unknown, however would be worth investigating.

(b) Biological records of microplastics in the Arctic

Records of plastic ingestion by Arctic biota exist for seven species, from a total of 15 papers. Results are summarised in Table 1. Records are most abundant for seabirds (four species). The species for which records are most numerous is the northern fulmar, which is likely a combination of their high vulnerability to plastic ingestion (Van Franeker et al. 2011) as well as the fact that studies in the Arctic have focused on fulmars as a study species (Trevail et al. 2015). Note that plastic ingestion studies typically do not distinguish between size categories of pieces, however include microplastics (Figures 2-4).

Biological monitoring can be a very valuable indicator of oceanic pollution levels. A review of two long-term data sets shows close similarities between trends in plastic pollution in stomachs of fulmars from the North Sea and plastic concentrations in the sub-tropical oceanic gyre in the North Atlantic (Van Franeker and Law 2015). In both monitoring sets, the proportion of industrial plastics have decreased since the early 1980s, with a time lag from the North Sea to the North Atlantic gyre (Van Franeker and Law 2015).



Figures 2-4: Plastic stomach contents of three northern fulmars from Svalbard in 2013. Scale bar represents 1 cm. (Trevail et al. 2015)

Table 1: Plastic ingestion by animals in the Arctic, as defined by the area north of 66˚ 34'N.

Species	Location	Years	Incidence of plastic ingestion	Average mass plastic per individual	References
Seabirds					
Northern fulmar *Fulmarus glacialis*	Svalbard, Europe. 78.3˚N, 16.1˚E	1982-1984	29%		Mehlum and Gjertz 1984; Gjertz et al. 1985; Lydersen et al. 1985
		2013	87.5%	0.08g	Trevail et al. 2015
	Bjørnøya, Svalbard, Europe 74˚24'N, 19˚0'E	1983	82%		Van Franeker 1985
	Jan Mayen, Europe, 71˚0'N, 9˚0'W	1983	79%		Van Franeker 1985
	East Canadian Arctic. 67-74˚N, 62-90˚W	2002 - 2008	Latest: 84%	Latest: 0.09g	Mallory et al. 2006; Mallory 2008; Provencher et al. 2009
Brünnich's guillemot/ Thick-billed murre *Uria lomvia*	Svalbard, Europe. 78.3˚N, 16.1˚E	1982-1984	20%		Mehlum and Gjertz 1984; Gjertz et al. 1985; Lydersen et al. 1985
	Southwest Greenland, Europe	1988-1999	6%		Falk and Durinck 1993
	Prince Leopold Is. Canada. 74˚0'N, 90˚0'W	2008	8%	0.0017g	Provencher et al. 2010
	The Minarets, Canada. 67˚0'N, 61˚8'W	2007-2008	6%	0.0003g	Provencher et al. 2010
Little auk/dovekie *Alle alle*	Svalbard, Europe. 78.3˚N, 16.1˚E	1982-1984	11.6%		Mehlum and Gjertz 1984; Gjertz et al. 1985; Lydersen et al. 1985
	Hakluyt Island, Greenland, Europe 77˚25'N 72˚42'W	1997-1998	8.7%		Pedersen and Falk 2001
Kittiwake *Rissa tridactyla*	Svalbard, Europe. 78.3˚N, 16.1˚E	1982-1984	1.9%		Mehlum and Gjertz 1984; Gjertz et al. 1985; Lydersen et al. 1985

Cetaceans					
Bowhead whale, *Balaena mysticetus*	Baffin Bay, Canada				Finley 2001
	Beaufort Sea, Alaska, USA				Lowry 1993
Sperm whale, *Physeter macrocephalus*	Between Iceland and Greenland, Europe 62-67°N 24-30°W	1977-1981	<10%		Martin and Clarke 1986
Fish					
Greenland Shark, *Somniosus microcephalus*	South Greenland, Europe 59-76°N,	2012	8.3%		Nielsen et al. 2013

The four avian species with records of plastic ingestion in the Arctic have varying foraging ecologies, reiterating that plastic pollution can effect a wide range of ecological niches. Northern fulmars are ubiquitous surface feeders, typically foraging on small pelagic fish, squid, worms and jellyfish at the ocean surface, hence their vulnerability to consuming plastic that is also floating near the ocean surface (Donnelly-Greenan et al. 2014). Fulmars also exploit fisheries discards as a food source, likely enabling high populations towards the southern extent of their distribution (Phillips et al. 1999). Fulmars typically forage around 50 km from the colony during the breeding period (Thaxter et al. 2012), with exceptional individuals undertaking extended trips to offshore feeding areas on the mid-Atlantic ridge 2400 km away (Edwards et al. 2013). Fulmars can migrate substantial distances, although remain relatively sedentary once in their winter area (Mallory et al. 2008). Brünnich's guillemots (or thick-billed murre), *Uria lomvia,* dive to depths of approximately 50 metres to forage (although records exist for >100 m), typically relying on schooling fish, ice-associated crustaceans or benthic crustaceans (Barrett et al. 1997; Mehlum et al. 2001; Mehlum 2001). Brünnich's guillemots have a foraging range of approximately 50 km during the breeding period (Benvenuti et al. 2002) and have winter in coastal shelf or pelagic areas (Gaston et al. 2011). Little auks (or dovekies), *Alle alle,* are also a diving forager, although feed at shallower depths than Brünnich's guillemots (average 10m, up to 30m recorded) predominately on *Calanus* copepods (Steen et al. 2007; Harding et al. 2009). Little auks adopt a bimodal foraging strategy during the breeding period, foraging both in the vicinity of the colony and up to 150 km away from the colony (Steen et al. 2007). Little auks migrate to productive areas during winter to continue feeding on copepod stocks (Fort et al. 2010). Kittiwakes, *Rissa tridactyla,* forage on schooling pelagic fish near the ocean surface (Harris and Wanless 1997). Indeed, kittiwakes have served as an indicator of fisheries health in the North Sea since the decline in lesser sandeel, *Ammodytes marinus*, have had dire consequences for kittiwake populations (Lewis et al. 2001). Foraging trips extend to approx.-imately 70 km during the breeding period (Daunt et al. 2002) although average around 25 km (Thaxter et al. 2012) whilst overwinter migration extends to ocean basin scale, with 80% of northeast Atlantic kittiwakes migrating to west of the mid-Atlantic ridge (Frederiksen et al. 2012).

If sampled immediately after migration, stomach plastic contents of Arctic seabirds could be representative of plastic pollution levels in their previous foraging area. Plastic residence times in the stomach are however relatively short (75% turnover within one month) and therefore ingested plastic is a relatively robust indicator of local pollution levels (Van Franeker and Law 2015).

The three pelagic species also occupy a variety of foraging niches from planktiverous to predatory behaviour. Bowhead whales, *Balaena mysticetus,* are permanent residents of the Arctic Ocean, occupying seasonally ice covered areas to feed mainly on calenoid copepods, euphausiids and planktonic organisms, and occasionally on epibenthic amphipods (Hazard and Lowry 1984; Lowry 1993). Sperm whales, *Physeter microcephalus,* dive to forage on predominately cephalopods as well as some fish species (Clarke et al. 1993; Watwood et al. 2006). Greenland sharks, *Somniosus microcephalus,* are an opportunistic apex predator in the Arctic, foraging on benthic fish, mammals, crustaceans, cephalopods and gastropods (MacNeil et al. 2012; Nielsen et al. 2013) as well as scavenging for offal from the Norwegian minke-whaling industry (Leclerc et al. 2011). Greenland sharks have a wide distribution throughout the water column, from 100-1200 m deep (Nielsen et al. 2013).

The effects of plastic ingestion are covered later in this review, nevertheless the population consequences are largely unknown at present. The range of ecological niches that are vulnerable to plastic ingestion in the Arctic, however, highlight the potential for widespread vulnerability of Arctic ecosystems to detrimental effects of plastic pollution.

Although microplastic records in the Arctic are most numerous from biological studies, there is not enough information to discern any spatial or temporal trends. Plastic ingestion levels in the Arctic are generally lower than at lower latitudes, however are not as low as would be expected given relatively low human activity in the region (Trevail et al. 2015). This is likely as a result of ocean currents transporting plastic over large distances from regions of higher pollution.

Records of seabirds in the sub-Arctic with plastic ingestion include many species also found in Arctic ecosystems, including little auks/dovekies, *Alle alle* (Fife et al. 2014), common and Brünnich's/thick-billed guillemots, *Uria aalge* and *U. lomvia* (Bond et al. 2013), great and sooty shearwaters, *Puffinus gravis* and *P. griseus* (Bond et al. 2014), short-tailed shearwaters, *Puffinus tenuirostris* (Vlietstra and Parga 2002; Yamashita et al. 2011), northern fulmars, *Fulmarus glacialis*, (Kühn and Van Franeker 2012; Bond et al. 2014), fork-tailed and leach's storm-petrels, *Oceanodromo furcata* and *O. leucorhoa,* pelagic cormorant, *Phalacrocorax pelagicus*, mew gull, *Larus canus,* black- and red-legged kittiwakes, *Rissa tridactyla* and *R. brevirostris,* Cassin's parakeet and crested auklet, *Aethia psittacula* and *A. cristatella,* pigeon guillemot, *Cepphus columba,* horned and tufted puffins, *Fratercula corniculata* and *F. cirrhata* (Robards et al. 1995), common eider, *Somateria mollissima sedentaria*, Atlantic puffin, *Fratercula arctica*, (Bond et al. 2014).

(c) Microplastics in Arctic sea ice

To date, one study has quantified plastic concentration in Arctic sea ice (Obbard et al. 2014). Results showed varying concentrations of microplastics in ice cores, ranging from 38 to 234 pieces per m^3: considerably higher than concentrations in the most highly polluted oceanic gyres (Obbard et al. 2014). Microplastic levels in sea ice may be higher than surrounding water bodies because of the concentrating effect of the scavenging phenomenon that accompanies sea ice growth (Obbard et al. 2014). Methods used by Obbard et al. (2014) would benefit from validation, however the warning that comes with the study still holds: global climate change and rapidly melting sea ice could lead to release of a legacy of plastic pollution into the Arctic Ocean.

(d) Sediment, benthic and coastal records of microplastics in the Arctic

This review found no records of microplastics in sediment, benthic or coastal accounts of marine litter in the Arctic. Records for macro-plastics are given below, since they indicate potential for microplastic pollution.

At the deep-sea research station, HAUSGARTEN, in the eastern Fram Strait near Svalbard (79˚N), presence of marine litter in visual surveys has increased over the study years (2002-2011) (Bergmann and Klages 2012). Although methods are only able to account for macro-litter (Figure 5), results indicate the potential presence of both primary microplastics and secondary microplastics when the items observed inevitably breakdown and fragment.

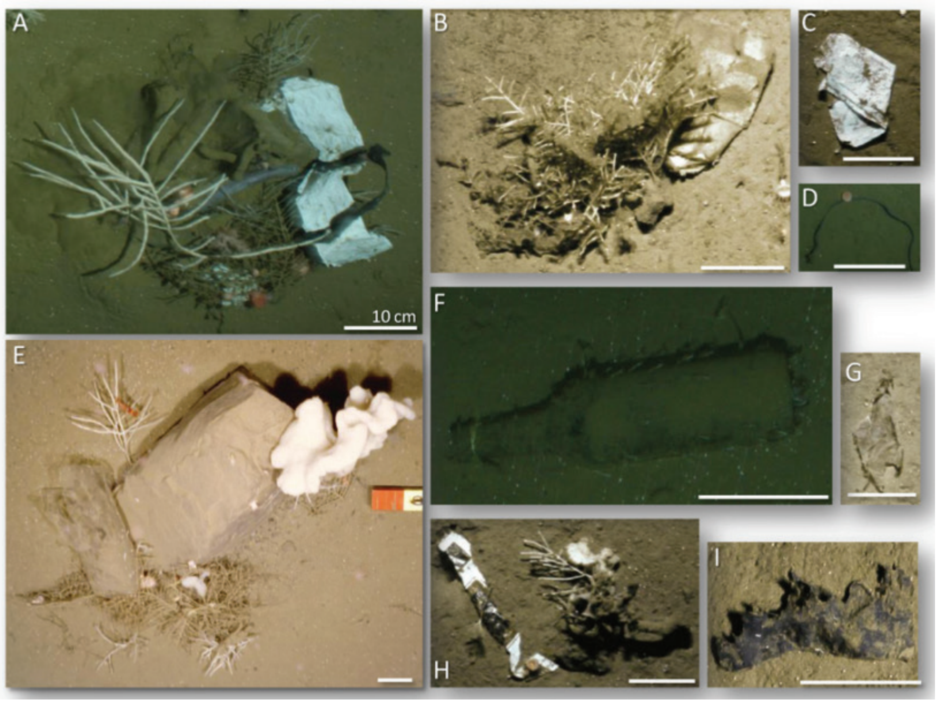


Figure 5: From Bergmann and Klages (2012): Examples of types of litter and of interactions between litter and megafauna recorded from seafloor photographs: (A) polystyrene, fragment of plastic bag and black material entangled with *Cladorhiza gelida* and *Caulophacus* fragments, rubber band with actinian; (B) cardboard/paper packaging entrapped with *C. gelida*; (C) sanitary towel; (D) rope colonised by actinian (cf. Amphianthus); (E) plastic bag entrapped with *Cladorhiza gelida* and dropstone; (F) beer bottle colonised by hydroids and *Bathycrinus carpenterii*; (G) fragment of plastic bag; (H) tinfoil packaging colonised by actinian; and (I) black material resembling roof paper.

The Governor of Svalbard, Sysselmannen, has been undertaking annual beach-cleans in Svalbard since 2000 in accordance with OSPAR monitoring methods. In the subsequent 11 years, volunteers collected 1,083 m^3 of litter from three stretches of beach (Hals et al. 2010). Although records predominately consist of macro-litter (Hals et al. 2010), again it indicates the presence of both primary and secondary microplastics.

Figures 6 & 7: Plastic on the shores of Svalbard, of which eventual breakdown will result in microplastics. Pictures © Rolf Strange (left) and Norwegian Polar Institute (right).

Effects of microplastics

The deleterious effects of plastic pollution, and the potential for adverse effects in the Arctic, are numerous. Floating debris can act as a transport vector for pollutants (Zarfl and Matthies 2010), invasive species (Barnes 2002) and harmful algae. These may act as important stressors with threats to biodiversity, particularly under climate warning scenarios (Serreze et al. 2007). Furthermore, as a result of their small size and presence across a wide range of environments, a wide range of taxa can ingest microplastics from zooplankton, near the base of the food web (Cole et al. 2013), to commercially valuable species fished for human consumption (von Moos et al. 2012; Mathalon and Hill 2014), and marine predators such as seabirds (Trevail et al. 2015) (Figure 8).

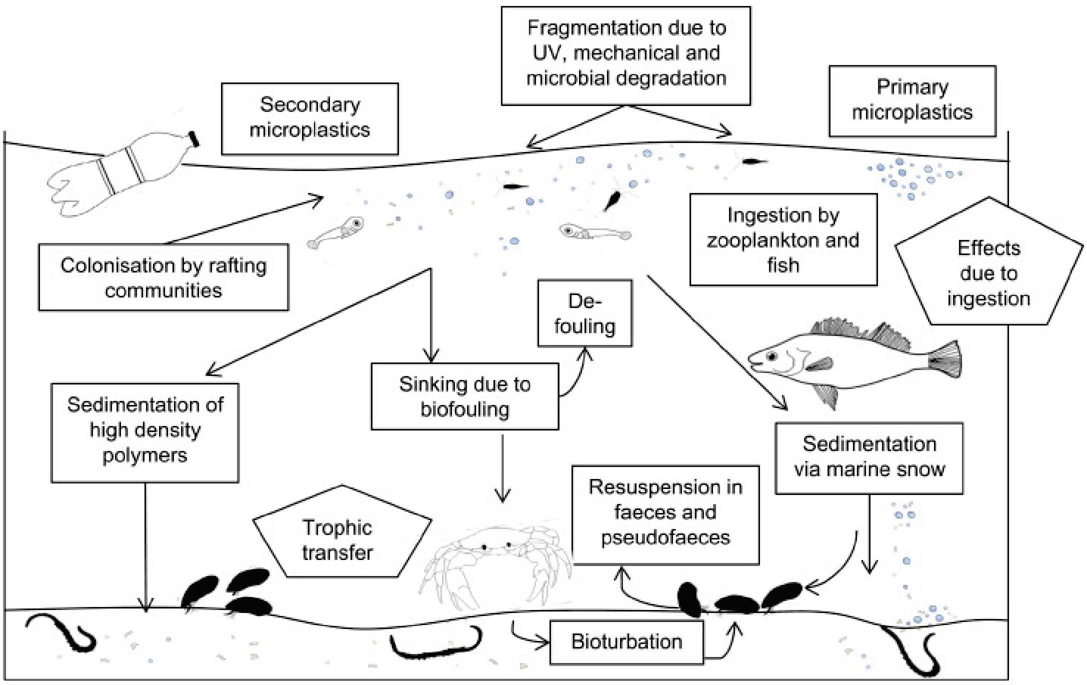


Figure 8: From Wright et al. (2013), microplastic pathways in the marine environment.

Microplastics may pose a mechanical threat to smaller organisms that ingest them, such as zooplankton. Experimental studies have proven that microplastic ingestion by zooplankton can inhibit normal feeding activity (Cole et al. 2013). For larger organisms, the impacts of microplastic ingestion are likely to be related to chemical effects. Microplastics typically contain up to six-times the amount of contaminants as found in sediments, both from within the particles (e.g. colourants, flame-retardants, and softeners used within plastic products) and adsorbed to the surface of the particles from seawater (Teuten et al. 2007). Ingestion of microplastics and the uptake of associated chemicals will likely have adverse physiological effects, although the population consequences are unknown: a valuable area for further study (Thompson et al. 2004; Arthur and Baker 2011; Van Franeker et al. 2011; Lindborg et al. 2012; Verreault et al. 2013; Tanaka et al. 2013). Furthermore, Erren et al. (2009) suggested that plastic pollution is causing increased incidence of wildlife cancer.

For many taxa, exposure to organic pollutants of high environmental concern may occur naturally via bioaccumulation (Borgå et al. 2001), however direct consumption of plastic is considered an additional source (Ryan et al. 1988; Colabuono et al. 2010; Tanaka et al. 2013). Arctic wildlife is typically high in lipids to survive colder temperatures, which may render them particularly vulnerable to the effects of organic contaminants that are generally highly lipid-soluble (Borgå et al. 2001) such as PCBs, PBDEs and pesticides. Such pollutants have been proven to result in a plethora of detrimental effects, including changes in enzyme activity (Verreault et al. 2013), disruptions of endocrine systems (Nøst et al. 2012; Verreault et al. 2013), decreased immunity (Sagerup et al. 2009; Sagerup et al. 2014), behavioral differences (Bustnes et al. 2001), reduced reproduction (Bustnes et al. 2003) and decreased adult survival (Gabrielsen et al. 1995; Bustnes et al. 2003).

In March 2004, exceptionally large numbers of beached northern fulmars were found around the southern coasts of the North Sea, most concentrated along the coasts of Belgium, northern France, Germany, the Netherlands and southern England (Van Franeker 2011). Above average numbers also occurred as far north as southern Norway. Many of the beached fulmars had feathers in a poor condition, having arrested both tail and primary moult the previous October, and an unusually large number were adult females (Van Franeker 2011). Increased mortalities continued into May and June, including several individuals carrying eggs that were found dead at large distances from any colonies. Such findings are contrary to the usual behaviour of long-lived petrel species to abandon reproduction if adult survival is threatened, for example by poor body condition (Chastel et al. 1995). Feather moult, feather condition, and reproductive behaviour are all regulated by the endocrine system (Van Franeker 2011). The observed disruption of these could therefore be indicative of a hormonal disruption from chemicals associated with ingested plastic (Van Franeker 2011). At the time, no funding was available to test this hypothesis and therefore this interpretation is merely speculative.

In the March 2004 mortality event, the delay in feather moult showed that hormone disruption began in the previous autumn and persisted until a threshold level of tissue chemical load was reached at a time of high-energy demand. Such hormonal disruption could have population effects if widespread, such as the 2004 fulmar wreck (Van Franeker 2011). It is therefore important that if related to plastic pollution, any correlative link that exists between cause and effect is determined. This will enable policy makers to be informed about the adverse effects of chemicals entering the environment, as well as the magnitude and extent of the threat posed to marine ecosystems by plastic pollution (Depledge et al. 2013; Rochman et al. 2013).

Recommendations for the future

The need for further study in the Arctic is evident. Comprehensive research into microplastic pollution in different ecosystems in the region will provide information on the extent of Arctic biota at risk. Research priorities are defined below:

1. Perhaps the most important area for future study is research into alternative processes, products and protocols to reduce the input of plastics into the marine environment. This can be undertaken by a variety of sectors, for example the public sector can promote alternatives to excessive plastic use and a change of human behaviour to reduce littering and change consumer decisions. Different industries can work on aspects such as waste management to tackle both irresponsible and accidental losses of plastic to the environment. Collaboration between stakeholders will hugely benefit this process.
2. Secondly, research into effective mitigation methods to remove plastic from the marine environment without detriment to local biota will be valuable to reverse the problem for the benefit of current economies and future generations.
3. Quantification of ocean surface plastic concentrations in the Arctic would benefit our global understanding of the magnitude of plastic pollution and could explore the sixth gyre hypothesis suggested in Van Sebille et al. (2012).
4. Further study of microplastics in Arctic sea ice can confirm methods in Obbard et al. (2014) and would improve our awareness of the plastic legacy that awaits release into the Arctic Ocean with sea ice melt.
5. Continued study of plastic ingestion by Arctic biota, particularly northern fulmars, will provide valuable monitoring of plastic litter in the region.
6. Understanding riverine inputs of plastic pollution into the Arctic could aid mitigation actions in the region.
7. Further understanding of the chemical consequences of plastic litter will develop understanding not only the potential effects for Arctic biota, but also the possible consequences for human health via consumption of contaminated seafood.
8. Efforts to continuously improve microplastic quantification and uniform classification will benefit future studies.

In the case of the Arctic, a lack of quantitative information about plastic pollution should not hold back any action to reduce levels of marine litter. Enough is known about the dire state of the marine environment worldwide with respect to marine litter, as well as the persistence of the problem and the huge potential for negative effects, to give sufficient cause for action. There are so many benefits of reducing the problem of marine litter, including restoration of ecosystem aesthetics, functions and services and a reduction of the economic costs and risks to the health of the environment and humans. Public opinion against marine litter is gaining momentum, particularly in coastal communities. Influential stakeholders, including scientists, policy-makers and industries, have a responsibility that comes with knowledge and power to act now for the benefit of future generations.

All photographs: Bo Eide,
Tromsø kommune

Marine litter collected in a small cove on Sessøya island, west of Tromsø.

Part of a trawl net, and other assorted fisheries related marine litter washed ashore on Kvaløya, west of Tromsø.

Microplastics in the making. In the surf zone, marine litter is broken down into smaller and smaller pieces.

Littered coastline on Sandøya, north west of Tromsø.

From Rekvika, an extremely littered beach on Kvaløya. This beach is now cleaned twice yearly and the findings registered, as part of the OSPAR beach litter registration scheme.


Registration of collected marine litter in Rekvika.


Collected marine litter on board the Coast Guard vessel KV Farm.

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033 KORTRAPPORT / BRIEF REPORT
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