Check for updates

Plastic pollution in the Arctic

Melanie Bergmann [1 ✉], *France Collard[2], Joan Fabres* [3,4], *Geir W. Gabrielsen[2],*
Jennifer F. Provencher[5], Chelsea M. Rochman[6], Erik van Sebille [7,8] *and Mine B. Tekman[1]*

Abstract | Plastic pollution is now pervasive in the Arctic, even in areas with no apparent human activity, such as the deep seafloor. In this Review, we describe the sources and impacts of Arctic plastic pollution, including plastic debris and microplastics, which have infiltrated terrestrial and aquatic systems, the cryosphere and the atmosphere. Although some pollution is from local sources — fisheries, landfills, wastewater and offshore industrial activity — distant regions are a substantial source, as plastic is carried from lower latitudes to the Arctic by ocean currents, atmospheric transport and rivers. Once in the Arctic, plastic pollution accumulates in certain areas and affects local ecosystems. Population-level information is sparse, but interactions such as entanglements and ingestion of marine debris have been recorded for mammals, seabirds, fish and invertebrates. Early evidence also suggests interactions between climate change and plastic pollution. Even if plastic emissions are halted today, fragmentation of legacy plastic will lead to an increasing microplastic burden in Arctic ecosystems, which are already under pressure from anthropogenic warming. Mitigation is urgently needed at both regional and international levels to decrease plastic production and utilization, achieve circularity and optimize solid waste management and wastewater treatment.

[1]*Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany.*

[2]*Norwegian Polar Institute, Fram Centre, Tromsø, Norway.*

[3]*GRID-Arendal, Arendal, Norway.*

[4]*Present address: SALT, Svolvær, Norway.*

[5]*National Wildlife Research Centre, Environment and Climate Change Canada, Ottawa, Ontario, Canada.*

[6]*Department of Ecology and Evolutionary Biology, University of Toronto, Toronto, Ontario, Canada.*

[7]*Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, Netherlands.*

[8]*Freudenthal Institute, Faculty of Science, Utrecht University, Utrecht, Netherlands.*

✉*e-mail: Melanie.Bergmann@ awi.de*

https://doi.org/10.1038/ s43017-022-00279-8

Industrial plastic production has grown rapidly since the 1950s, reaching 368 million tonnes globally per year by 2019 (REF.[1]). Because of its low price, plastic has become one of the most widely used materials, especially in the packaging industry, and now forms an integral part of municipal waste. Every year, 19–23 million metric tonnes of mismanaged plastic waste are transferred from land-based sources to water globally[2].

As plastics are designed to be durable, they persist in the environment for long periods of time and become widely dispersed[3,4]. Therefore, plastic is a planetary boundary threat[5,6], especially once it fragments into microplastic and nanoplastic (size ≤5 mm and ≤1 μm (REF.[7]), respectively) due to sunlight, mechanical abrasion, biotic interaction, wave action[8] and temperature fluctuations. Plastic is also extensively used in maritime operations such as fishing, aquaculture, shipping and offshore operations, leading to substantial additional leakage into marine environments. Although millions of tonnes of plastics enter the oceans annually, it is currently unknown where in the ocean 99% of the small plastic debris ends up[9], pointing to yet unaccounted for accumulation areas[10].

Polar regions are still perceived as pristine. However, in the past five years, high levels of plastic pollution have been found in the Arctic (FIG. 1). The formation of a sixth accumulation area in the Nordic Seas has been suggested by model projections[11] and is corroborated by an increase in marine debris over time[12,13] and comparatively high microplastic concentrations in the Arctic[14,15]. This evidence has prompted a Protection of the Arctic Marine Environment (PAME, Arctic Council) working group desktop study on marine litter and microplastics in the Arctic[16] to gauge the need for a Regional Action Plan, which, in turn, led to a mandate to assess the status and trends by the Arctic Monitoring and Assessment Programme[17].

In this Review, we describe the sources of Arctic plastic debris, its distribution and its effects on Arctic biota, as well as knowledge gaps and mitigation with a broad, pan-Arctic view, complementing previous reviews focused on plastic pollution effects on Arctic biota[18], such as seabirds[19], or with differential geographic focuses[20–22]. We also discuss interactions between climate change and plastic pollution, as plastic pollution likely adds to the impacts of climate change, which has caused a three times faster increase in Arctic temperatures compared with the global average[23].

Sources of Arctic plastic debris

As much of the Arctic is sparsely inhabited, relatively low local plastic pollution inputs would be expected. Yet, there are widespread observations of plastics in the region. Most model simulations and data suggest that a substantial proportion originates from the North Atlantic[9,24] and the North Pacific[25,26] (FIG. 1). Rivers were

Key points

- The widespread plastic pollution in the Arctic originates from both local and distant sources.
- Concentrations of plastic in the Arctic vary widely, with greater accumulation in certain hotspots, but are generally similar to those of more densely populated regions.
- Plastic has infiltrated all levels of the Arctic food web, including many endemic species, with largely unknown organismal impacts.
- In the fast-changing Arctic, plastic pollution adds to the effects of climate change in terms of growing sources, transport processes, potential feedback loops and ecological consequences.
- Mitigation of both local and distal plastic pollution is needed to prevent further ecosystem degradation.

also suggested as a pathway of microplastic pollution in the Arctic[27]. Although the Arctic Ocean contains only ~1% of the global ocean volume, it receives >10% of the global river discharge[28]. Transport of plastic pollutants to and in the Arctic is governed by processes from large-scale ocean currents to small-scale phenomena, such as windrows and sea ice drift[29,30] (FIG. 2). Model simulations and data from global studies on microfibres suggest that some regions of the Arctic are accumulation areas for plastic pollutants[11,14,15]. In order to support the design of efficient regulatory schemes to mitigate plastic pollution, it is common to distinguish between land-based and sea-based sources from both local and distant origins, as discussed here.

Local sources of plastic include the key sectors of maritime activity in the Arctic, such as hydrocarbon exploration, aquaculture and ship traffic, including cruise tourism and fisheries (FIG. 1). For example, abandoned, lost or otherwise discarded fishing gear is a major source of plastic debris, especially in the Greenland, Norwegian and Barents Seas[31,32], Kara Sea[33] and subarctic North Atlantic[34,35] and North Pacific oceans[36,37]. On the beaches of Svalbard, plastic debris from fisheries accounted for 27–100% of beach litter[38–41]. Fisheries are also an important source at Novaya Zemlya, especially in terms of strapping bands[42], and at Franz Josef Land, Barents Sea, where they accounted for 51% of the debris[31], although they do not appear to be major sources in the Canadian Arctic[43]. Recognizable items from the Eurasian Arctic originated mostly from Russian and Scandinavian trawlers but also from the UK, Iceland, Faroe Islands, the Netherlands, Germany, Italy, Spain, Canada, Argentina, Brazil and the USA[16,32,39,44]. Fibres or threads from fishing nets were the most important source of microplastics in the Barents Sea[45] and the second most abundant type of microplastics in southwest Greenland[46]. Notably, 80–90% of the fishing nets found on Svalbard had been discarded deliberately by fishers after mending nets[32]. Much of the material used is positively buoyant, such that it drifts and washes ashore. Some of the items could also come from the intensifying aquaculture, but it is difficult to differentiate between fishing and aquaculture sources. Fisheries regulations such as conservation zones and fishing permits reduce the number of fishers operating in an area and can help to reduce fisheries-related debris, as shown in the 1980s in Alaska[47,48].

Another source is plastic debris from domestic sources, as evidenced by reports of bottles, containers, plastic bags and fabrics[31]. However, because such items are also used on ships, it is difficult to attribute such plastics to land-based versus sea-based sources, and input from sea-based sources was rated more important than land-based sources in the Arctic[24]. For example, large food containers amongst the household plastics found on northwest Svalbard point to the disposal of galley waste, which is of sea-based origin[32]. Litter quantities on the seafloor of the Fram Strait have been correlated with increasing activities in both the fisheries and the tourism sectors west of Svalbard[49]. The prevalence of fast-sinking glass debris on the deep Arctic seafloor also corroborates the importance of local sea-based sources[12]. Arctic ship traffic is due to increase as new and faster trans-Arctic routes open, and the shipping season extends as sea ice declines[50], potentially leading to increased local plastic inputs.

A major challenge to minimizing the input of waste from land into the ocean globally is the lack of adequate waste management facilities in coastal regions[51]. As Arctic population densities are low, waste collection and disposal is very basic. Recycling and baling facilities are rare and limited to large Arctic communities. Waste collection in larger communities often relies on community haul systems, whereas in small communities, it is typically by self-haul[52], which can be less efficient in preventing waste leakage into the environment. In some communities, traditional waste management solutions are landfills and uncontrolled dumpsites, sometimes next to the sea, and simple incinerators with no or limited flue gas treatment[53], as seen in Greenland[54] and Iqaluit, Canada[46,55]. Beach litter assessments[56] report input from inadequate waste facilities on the western shores of Greenland, where 90% of the Greenlandic population lives. In the Canadian Arctic, plastic litter densities were seven times higher near communities compared with more remote locations[43]. Open dumpsites and winter travel activities were identified as potential sources[43]. Numerous open waste disposal sites and abandoned landfills were also identified as an important source of plastic pollution distributed over the flat tundra by high winds of the Archangelsk region of Russia[57].

Microplastics are also widely distributed in the Arctic, transported by ocean and atmospheric currents and biota from both distant and local sources. Microplastics are either manufactured directly, for example, as pre-production pellets and microbeads, or formed through weathering and breakdown of larger plastic items. Data from the east Canadian Arctic suggest primarily distal sources of microplastic[46,58] or a combination of distant and local sources[46]. Substantial quantities of microfibres are found in sediments from the Canadian Arctic (1,930 fibres per kg dry weight), 51% and 20% of which were acetate cellulose and indigo denim, respectively, indicating long-range transport from southern wastewater source regions[59].

In other regions, local sources play a prominent role. High concentrations of microplastic in surface waters off west Greenland likely originate from the capital Nuuk, which harbours 18,000 inhabitants[60]. One local source could be effluent from sewage and wastewater treatment, which is often only mechanically treated or not

treated at all in Nuuk or Svalbard[60–62]. Indeed, large quantities of microplastic fibres are shed during washing of synthetic textiles[63], which are disproportionately much worn in cold polar regions and can leak into the ocean through inadequately treated wastewater. Local wastewater could also be one of the sources of microplastic in the White Sea basin[57]. Six million microlitter particles per hour were emitted into the ocean (≥100 μm, ~1,500 particles m⁻³) by a wastewater treatment plant in Reykjavik, Iceland, that only used mechanical treatment[64]. Exceptionally high levels of microplastic were also recorded from a sandy beach near Reykjavik[65], Iceland, which is located near a harbour and waste management facility. Therefore, even adequate waste management systems can act as sources if located close to the shore. Still, the introduction of mechanical and biological treatment at a wastewater treatment plant in Ny-Ålesund, Svalbard, has cut anthropogenic microparticle emissions by 99%, highlighting that systems are available to reduce further emissions from Arctic communities[66].

Other potential but poorly constrained local sources of microplastic include particles shed from ship paint, skidoos and other vehicles used on ice, as well as grey water released by rising numbers of ships operating in the area[67]. Paint-derived fragments were found in southwest Greenland[46] and dominated microplastic in water

samples from a National Wildlife Area on Baffin Island, hundreds of kilometres away from any major settlement, highlighting both local and distant sources in these coastal areas[68]. The expanding hydrocarbon industry could be another source of litter and microplastic — tube-dwelling worms and sediments taken near oil and gas platforms in the North Sea bore significantly higher microplastic burdens than those collected further away, especially the viscosity-enhancer polyacrylamide[69]. However, quantitative information on microplastic inputs from shipping and the hydrocarbon industry is lacking for the Arctic region.

Distribution and transport

Buoyant plastic can float with ocean surface currents to higher latitudes[24,70–72], with most plastic transport into the Arctic from the Atlantic[24] and modest transport of microplastic through the Bering Strait[73] (FIG. 2). Surface transport is accelerated by storms through wave-driven Stokes drift[74] or direct windage[75]. Mesoscale eddies also affect the transport of debris or other materials[76–80], as can subsurface transport of less buoyant plastic at depths below 50 m (REFS[81,82]). Biota can disperse plastic debris through ingestion, migration and egestion[83]. Some of the floating macroplastic becomes intercepted by uninhabited Arctic beaches of Svalbard[39–41], the Novaya
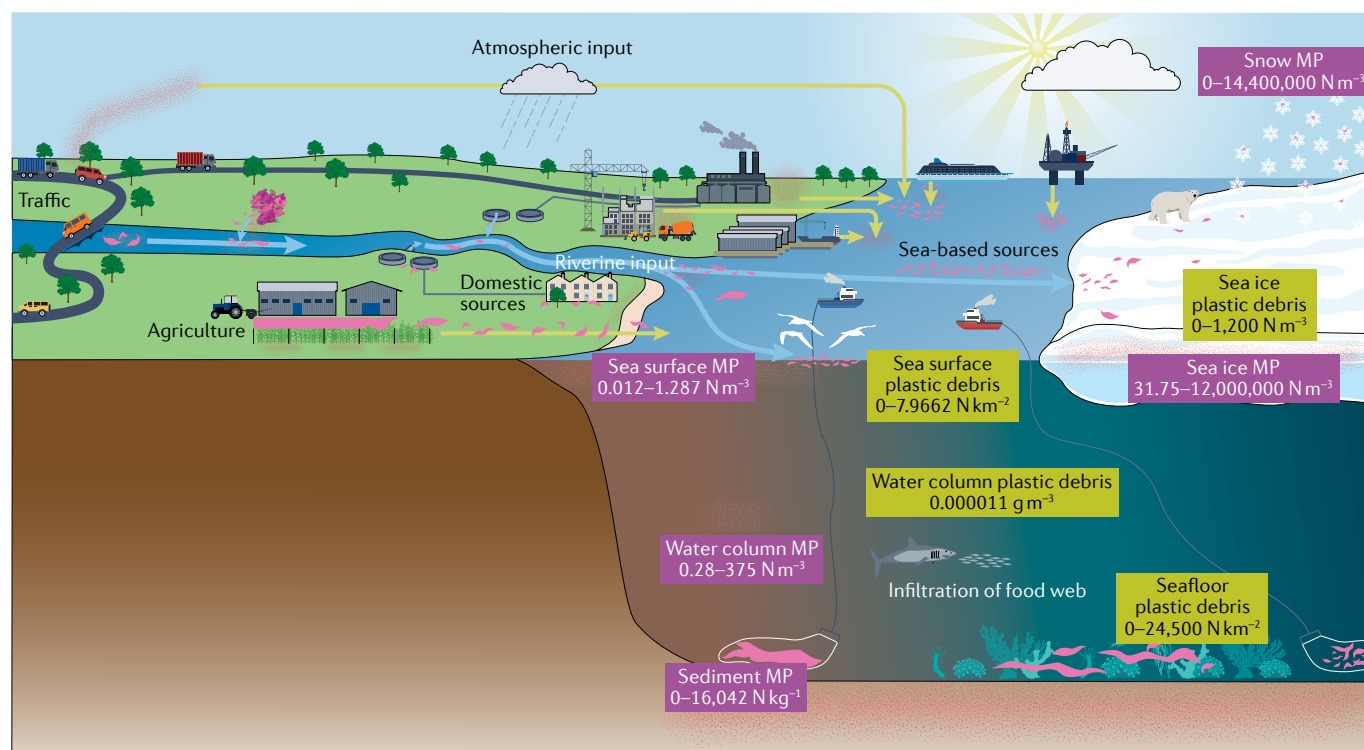

Fig. 1 | **Overview of the pathways of plastic pollutants into the Arctic Ocean from local and distant sources.** Plastic pollution can be generated by households, traffic, agriculture, wastewater treatment, landfills, illegal dumping, industry, shipyards, tourism, ships, fisheries and offshore industry, and be transported to and/or within the Arctic via the atmosphere, rivers, ocean currents, sea ice and eroding permafrost. The seafloor and sea ice are areas of plastic accumulation. The numbers in boxes refer to the abundance of plastic debris (green) or microplastics (MP, purple) in different ecosystem compartments. The ranges are based on data from 36 peer-reviewed studies reporting from 727 locations that were compiled in the database Litterbase[84] (more details on the data extraction process are provided in the Supplementary Information). The data in each compartment were converted to common units here, but the sampling and analytical methods used in different studies varied widely, as there are currently few standardized or harmonized procedures. For example, varying size detection limits in different studies likely introduced considerable variability in the ranges shown. Figure is adapted from AWI-Infographic, CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Fig. 2 | **The main pathways of pollution transport to the Arctic.** Plastic pollution is transported to the Arctic via atmospheric and aquatic circulation systems, which could promote their accumulation in certain areas. The main ocean currents that move pollution to and within the Arctic are shown as thin red, blue and green arrows, and the ten largest rivers that release 10% of the global river discharge into the Arctic Ocean are illustrated by thick blue arrows. Numbers in parentheses refer to average annual discharge in km³ (REF.[198]). The prevailing atmospheric circulation pattern is shown as translucent arrows. The solid and dashed blue lines indicate the main Arctic river basin and watershed, respectively. Figure adapted with permission from REF.[198], Elsevier.

Zemlya archipelago[79], the Russian Far East[44], Arctic Canada and west Greenland[43] at quantities ranging from 200 to 498,000 items km⁻² or from 8,830 to 523,680 kg km⁻² in terms of mass[84].

Much less is known about the transport processes of plastics within the Arctic because of scarce measurements. The available data show that plastic debris (0–7.97 items km⁻²)[13,72] and microplastics (0–1,287 particles m⁻³)[27,81,85] are widely distributed in Arctic surface waters (FIG. 3). Because of pollution transport from both the south (North Atlantic Current) and the north (Transpolar Drift), plastic quantities are likely higher in the Eurasian basin[73], which is corroborated by less weathered plastic microfibres and three times higher microfibre concentrations in the western Arctic[86].

However, more field data are needed to verify the lower concentrations on the Amerasian side. There, Pacific water does not spread over the whole Arctic Basin, as it circulates primarily around the Beaufort Gyre before leaving with the Atlantic water via the Canadian Arctic and past west Greenland[77] (FIG. 2). Still, it has been suggested that, during this transport, microplastic from the North Pacific enters the western Arctic, concentrates in the Beaufort Gyre and is carried to the central Arctic and Eurasian basins[26].

High microplastic loads in Arctic sea ice (31.75–12,000,000 particles m⁻³)[29,58] and models both suggest that sea ice drift supports basin-scale transport of ice-rafted plastic[26,73,87,88]. For example, during the formation of sea ice in the Kara and Laptev Seas, microplastic

from the sea surface becomes entrained in the ice matrix. In spring and summer, the sea ice breaks up and microplastics travel with ice floes to the Fram Strait via the Transpolar Drift[26,29] (FIG. 2), where the ice melts and releases its legacy to the water. The presence of ice algae and sticky extracellular polymeric substances in sea ice[89] could enable heteroaggregation of particles and, thus, promote their sinking to the seafloor[90], as could ballasting via sea-ice-derived cryogenic gypsum from under-ice *Phaeocystis* blooms[91]. These mechanisms could be one reason for the high quantities of microplastics (6,595 and 13,331 particles kg⁻¹ sediment) observed in the Fram Strait near the marginal ice zone[81,92]. Backward drift trajectories of ice cores taken in the central Arctic indicate that they originated from the Siberian shelves, western

and central Arctic[29,88] or circulate in the Beaufort Gyre[26]. Much of the sea ice is formed in regions[29] that receive water from Siberian rivers (FIG. 2).

Siberian rivers have huge catchment areas and cross big cities, industrial and agricultural areas, and receive wastewater effluents of unknown treatment level. Even further upstream, the Ob' and Tom rivers already contain high microplastic concentrations (44.2–51.2 particles m⁻³)[93]. The Severnaya Dvina river plays a major role in the transfer of microplastics to the White Sea[45] and river discharge was identified as the second largest source of the microplastic pollution in the Eurasian basin[27]. Yet, low levels were reported from three rivers feeding into the White Sea basin (0–6 particles m⁻³)[57]. Furthermore, litter quantities from the Russian Arctic indicate low riverine
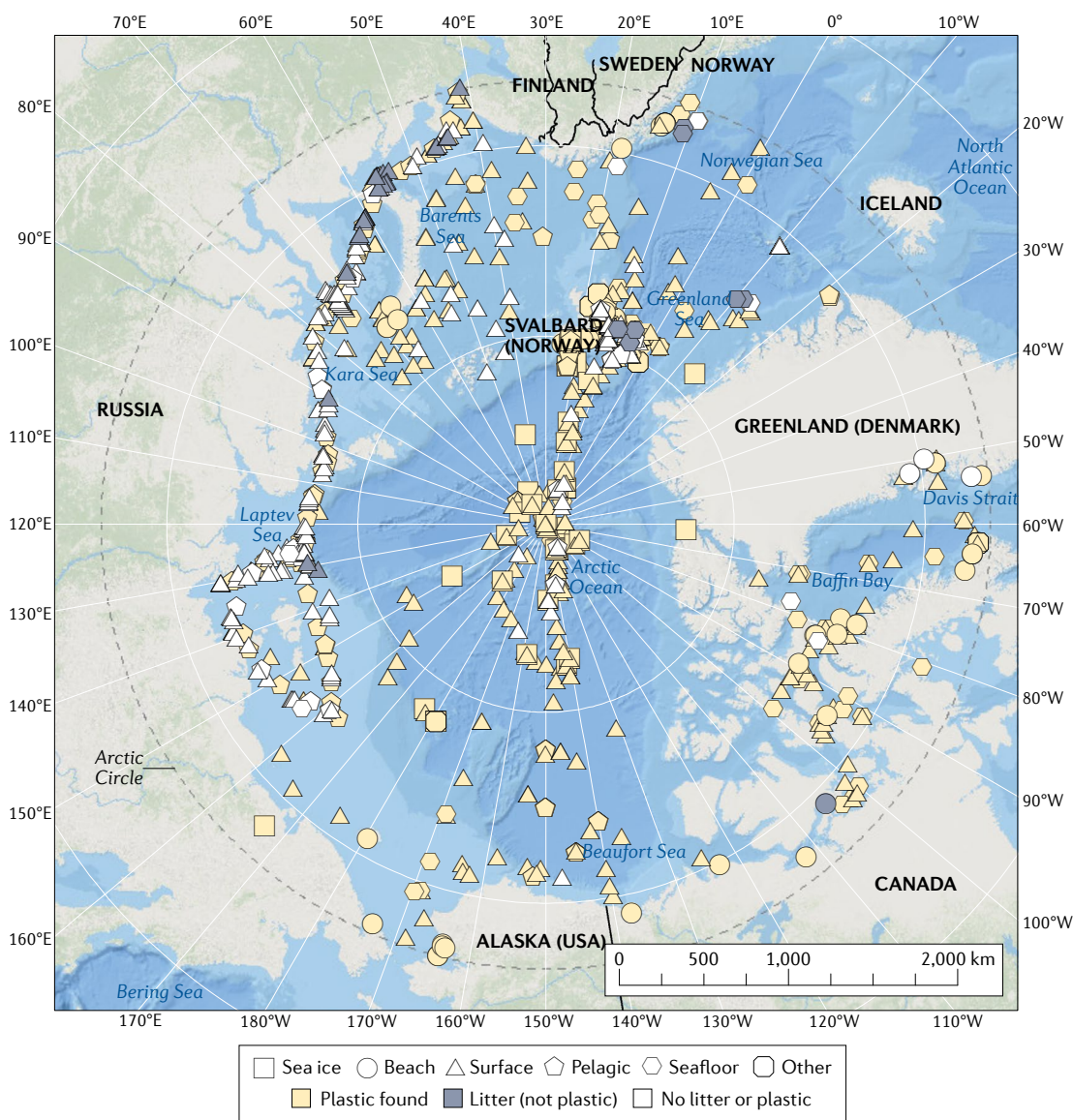

Fig. 3 | **Plastic pollution recorded in different Arctic ecosystem compartments.** Plastic pollution is widely spread in different ecosystem compartments of the Arctic Ocean. All yellow symbols refer to locations at the sea surface, water column, sea ice, seafloor and beaches where plastic pollution was recorded in 62 peer-reviewed studies compiled in the database Litterbase[84] (more details on the data extraction process are provided in the Supplementary Information). White symbols refer to locations where no litter was observed. Grey symbols refer to locations where other types of litter (but no plastic items) were observed.

contributions in autumn[72]. Still, during late spring, when river ice is melting and the greatest discharge into the ocean occurs, pollution levels could be higher.

Half of the plastic from municipal waste is denser than seawater[94] and sinks directly to the seafloor. However, even positively buoyant plastic is recorded in the water column and on the seafloor[81,95]. Mean quantities of 0.011 mg plastic debris m^{-3} prevailed in the upper 60 m of the Barents Sea[95]. Waters above the deep Arctic seafloor harboured microplastic concentrations of 0–375 particles m^{-3} (REFS[27,81,85]). Although no vertical trend was found in the Arctic Central Basin (0–375 particles m^{-3})[85], in the Fram Strait, the mean MP concentration decreased sixfold towards 1,000 m depth with profiles similar to those of particulate organic carbon[81]. Hence, biological processes such as incorporation in marine snow, fast-sinking aggregates of ice algae or phytoplankton and faecal pellets likely enhance the vertical flux of microplastic[81,96], along with vertical advection and diffusion in the water column[97]. Three-dimensional modelling of particles from the deep Fram Strait emphasized the importance of lateral advection and settling velocities in the vertical dispersal, with trajectories as long as 653 km (REF.[81]). Most of the modelled particles likely come from the North Atlantic, but sea ice appears to be a source of microplastic tracked back from the east Greenland slope[81]. Deep-water cascading events such as the Storfjorden overflow in Svalbard could also enhance downward particle flux[98].

Plastic pollution has been recorded from various regions of the Arctic seafloor, including the Norwegian Sea[99–101], Fram Strait[12,49,92,102], east Greenland slope[103], Barents Sea[95], central Arctic Basin[104], Bering and Chukchi seas[105] and east Canadian Arctic[58] (FIG. 3). However, unlike bottom trawls from the Chukchi and Kara Seas, trawls from the East Siberian and Laptev Seas returned no litter[33]. The former was attributed to fishing activities in the Barents Sea[33]. Quantities of plastic debris on the seafloor range between 0 and 24,500 items km^{-2} (REFS[12,49,100,101]) and have increased from 813 to 5,970 items km^{-2} between 2004 and 2017 in the Fram Strait[12]. The absence of light, low temperatures and stable conditions lead to degradation rates that are particularly low in the deep sea, as indicated by 30-year-old plastic recovered from the Sea of Japan without any signs of deterioration[106]. Bottom currents can carry microplastics on the seafloor to accumulation areas that also happen to be biodiversity hotspots[107]. In the Arctic deep sea, microplastic concentrations range between 0 and 16,041 particles kg^{-1} sediment[58,108] and rank amongst the highest measured concentrations globally.

Atmospheric transport is also an important transport pathway, as indicated by the presence of microplastic in snow samples from ice floes in the east Canadian Arctic[58], western Arctic[26], Svalbard, Fram Strait[109] and Icelandic ice cap[110] ranging from 0 to 14,400,000 particles m^{-3} (REFS[58,109]). Atmospheric transport could also be a pathway to lakes, although early evidence from four lakes in the Archangelsk region of Russia suggests low pollution levels (0–2 particles m^{-3})[20]. As with mercury pollution, atmospheric circulation patterns including the Icelandic Low, North American High, Aleutian Low and Siberian High could carry air masses with microplastic and nanoplastic from urban eastern and western Europe, North America, East Asia and Siberia to the Arctic, where they can fall out by wet and dry deposition and accumulate in the ocean, cryosphere and permafrost[111] (FIG. 2). Airborne microplastic emissions from car tyres and brakes could be as high as riverine or direct inputs of these sources to the ocean[112]. Models suggest that tyre-wear particle concentrations in Arctic snow range between 6 and 150 ng kg^{-1} for particles ≤10 μm and that Greenland and the Arctic Ocean are important receptor regions[112]. The ocean itself also appears to be a conduit of atmospheric transport, as indicated by microplastic in sea spray mist and onshore winds from the open Atlantic[113].

Interactions with Arctic wildlife

Pervasive contamination of plastic pollution in the Arctic has led to wildlife exposure to both macroplastic and microplastic pollution (FIG. 4). Wildlife and plastics interact through colonization or rafting on marine debris, ingestion, entanglement and smothering, affecting a total of currently 131 species in the Arctic (based on available information as of November 2021)[84]. Interactions can occur both at sea and on land, either with beached debris or with waste from open dumpsites[31,39,114].

Ingestion of plastics among Arctic species. Ingestion of plastic debris by organisms does not always lead to direct harm, but it creates the potential for malnutrition, internal injury, obstruction of the intestinal tract causing starvation or rupture, and potentially death[83]. Plastic ingestion has been reported across various regions of the Arctic (FIG. 4) across several levels of the food web, including in zooplankton from the east Canadian Arctic[58] and the Fram Strait[115]. A range of other marine invertebrates also ingest microplastic such as sea anemones, starfish, brittlestars, shrimps, crabs, whelks, bivalves[116–118], amphipods[119] and tube worms[69]. Plastic has been found in Arctic fish such as sculpin (*Triglops nybelini*)[120], saithe (*Pollachius virens*)[121], polar cod (*Boreogadus saida*)[120,122], Atlantic cod (*Gadus morhua*)[121,123,124] and Greenland shark (*Somniosus microcephalus*)[125,126]. Because fish are indicators of ecosystem health, important links in Arctic food webs and part of the human diet, further research on plastic contamination in Arctic fish is warranted.

Seabirds are amongst the most studied biota in terms of plastic pollution, both globally and in the Arctic. Early reports of plastic ingestion by herring gulls (*Larus smithsonianus*) and parakeet auklet (*Aethia psittacula*) date back to the 1970s[19]. A total of 51 species of seabirds breed in the Arctic region and the ingestion of plastic is widespread among them[19]. It was common among 12 seabird species from the Russian Arctic, for instance, ~60% of Chaun Bay gull nests containing boluses with plastic likely from a nearby dumpsite[31]. The northern fulmar (*Fulmarus glacialis*) is the most widely studied species for plastic ingestion in the Arctic and globally, and has been sampled in a handful of Arctic regions
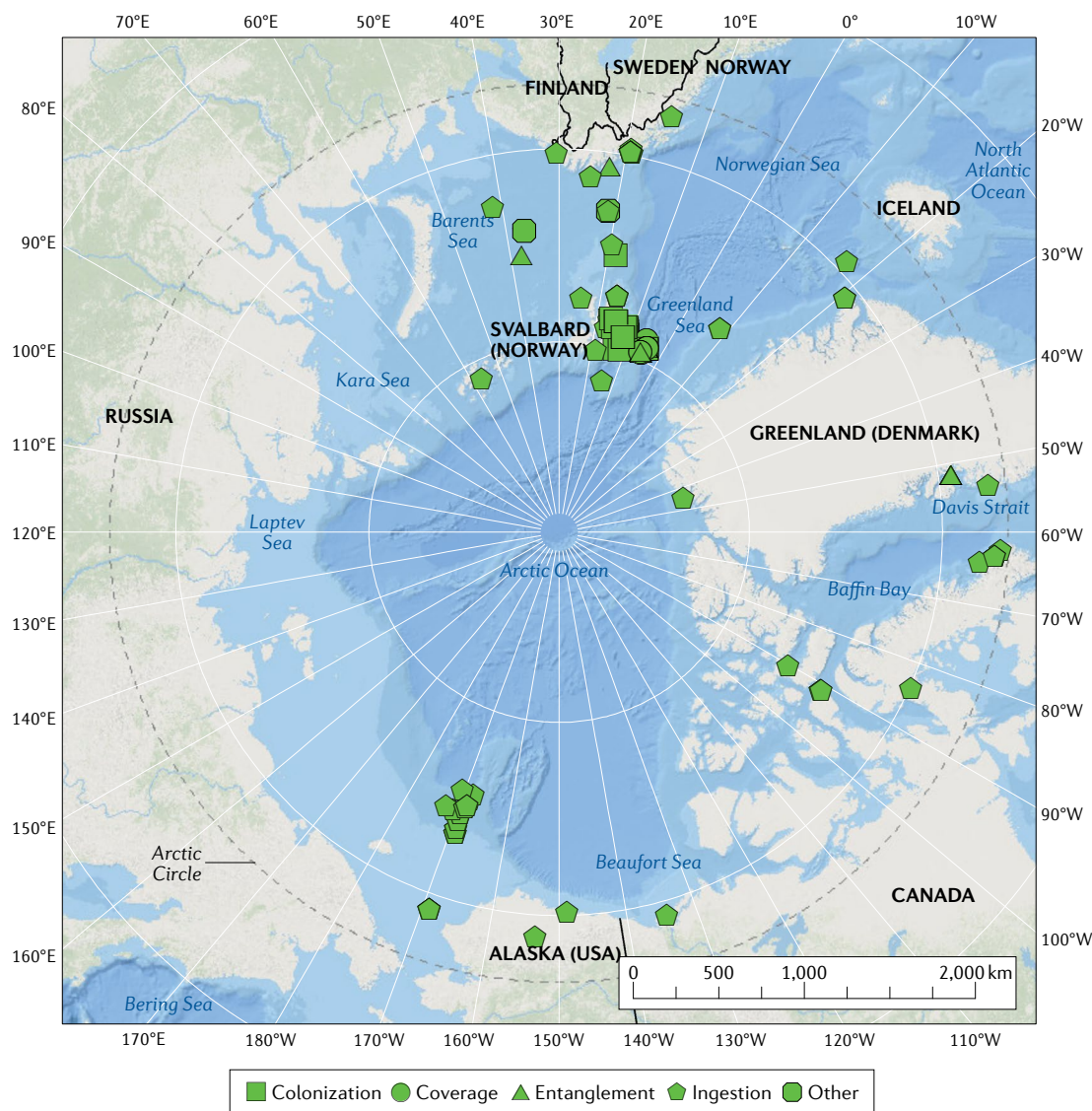
Fig. 4 | **Interactions between marine debris and Arctic biota.** Most interaction records refer to the ingestion of plastic and come from studies in the European and Canadian Arctic, with much of the Arctic region underrepresented in sampling efforts. All symbols refer to locations where interactions such as entanglement (nine species), ingestion (31 species), coverage of biota (five species), rafting on marine debris (72 species) and colonization (96 species) affecting a total of currently 131 species in the Arctic (as of November 2021) were recorded in 46 peer-reviewed studies compiled in the database Litterbase[84] (more details on the data extraction process are provided in the Supplementary Information).

repeatedly since 2001. Plastic ingestion levels vary with latitude, with fulmars sampled closer to the pole having lower levels (87% of the birds examined)[127] then their counterparts from other regions[128], which could reflect lower pollution levels in their feeding grounds.

There are only a few records of plastic ingestion by Arctic mammals[18], most of which are from whales, including sperm whales (*Physeter macrocephalus*)[129], belugas (*Delphinapterus leucas*)[130], fin whales (*Balaenoptera physalus*), bowhead whales (*Balaena mysticetus*)[131] and Stejneger's beaked whales (*Mesoplodon stejnegeri*)[132]. Only a handful of pinnipeds (seals, sea lions, walrus) have been examined in the Arctic region. No plastic pieces above 425 μm were detected in the stomachs of ringed seals (*Phoca hispida*), bearded seals (*Erignathus*

barbatus) and harbour seals (*Phoca vitulina*)[133]. Similarly, no plastic pieces larger than 5 mm were found in harp seals (*Pagophilus groenlandicus*) in Greenland, but two plastic sheets were reported in a 20-day-old hooded seal pup (*Cystophora cristata*) from the Greenland Sea[134]. Seventy percent of walrus faeces in Svalbard contained microfibres larger than 1 μm (REF.[135]). Although current knowledge suggests relatively low plastic ingestion levels of mammals overall, no firm conclusion can yet be drawn from the current data.

Plastics as a vector of chemicals. Plastic ingestion can expose organisms to harmful legacy pollutants from the environment or chemicals added during manufacturing[136] (FIG. 5). Consequently, there is a large body of work
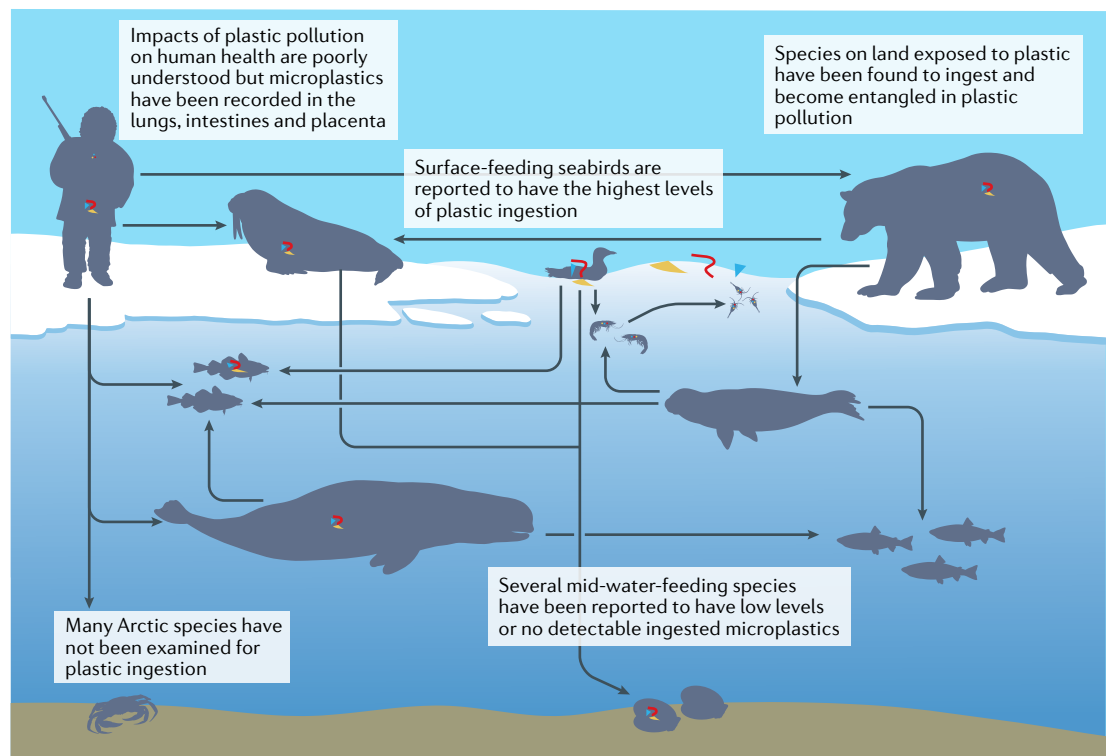
Fig. 5 | **Arctic food web and biotic interactions with plastic pollution.** Invertebrates, fish, birds and mammals in the Arctic have been examined for plastic ingestion (indicated by coloured symbols) and have been reported to become entangled in plastic litter. Although ingested microplastics have been found across several taxa, seabird species that feed at the sea surface are potentially the most vulnerable to accumulating plastic pollution. Adapted from an image courtesy of Julia Baak.

on plastics as a vector for chemicals to wildlife. In the Arctic, biota have been monitored for decades for environmental contaminants, including metals such as mercury and persistent organic pollutants (POPs). Although there are some indications that metals and POPs typically found in the environment are positively correlated with plastic ingestion in seabirds in non-Arctic regions[137], POP levels have, so far, not been linked with plastic levels in Arctic species[138,139]. However, research on northern fulmars suggests that ingested plastic can be a route for a congener of polybrominated diphenyl ethers[140]. More work is needed on the transport and fate of these contaminants to determine whether plastics are an important vector.

An area of emerging concern in the Arctic is the effect of plastic additives, chemicals directly linked to plastic pollution[141]. For example, ultraviolet (UV) stabilizers and substituted diphenylamine antioxidants — both plastic additives — were detected in ringed seals, northern fulmars and black-legged kittiwakes (*Rissa tridactyla*) from the Canadian Arctic[142]. These additives were also detected in seabird eggs from Alaska and northern Canada, indicating transfer to the next generation[142,143]. Although the effect of the small concentrations on seabirds is unknown, given that phthalates, UV stabilizers and substituted diphenylamine antioxidants are endocrine disruptors, more work is needed to understand how even small amounts affect the developmental stages of Arctic biota. Important to consider in the Arctic region is that many wild species are harvested. Future work should focus on examining plastic additives

in consumed species to inform links to human health as well as the health of Arctic biota.

Effects of plastic debris on Arctic wildlife. Entanglement in plastic debris can have deleterious effects, such as injury, restrained movement, starvation, strangulation and suffocation if air-breathing animals cannot return to the sea surface[83]. Entanglement has been reported for Arctic terns on Svalbard (*Sterna paradisaea*) and seven other seabird species in the Russian Arctic[31,39]. Thirteen seabird species have also been found to incorporate plastic debris in their nests[31], which can cause entanglement. Notably, almost all nests of two of the existing northern gannet (*Morus bassanus*) colonies at the Murman coast and 10% of an ivory gull (*Pagophila eburnea*) colony from the Kara Sea contained plastic[31]. Polar bears (*Ursus maritimus*), Arctic foxes (*Alopex lagopus*), bowhead whales, reindeer (*Rangifer tarandus*), bearded seals, harbour seals, Greenland halibut (*Reinhardtius hippoglossoides*), Atlantic cod and snow crabs (*Chionoecetes opilio*)[31,39,144–147] also experience entanglement.

Plastic debris can also act as a raft to transport animals from one location to another. Six percent of the plastic items stranded on Svalbard were colonized by bryozoans (*Membranipora membranacea*) and barnacles (*Semibalanus balanoides*)[148]. Macroalgae, bryozoans, barnacles (*Semibalanus* sp., *Lepas anatifera*) and blue mussels (*Mytilus* sp.) also inhabited beach debris on Svalbard[41]. Rafting of adult groups could favour dispersal over larval transport and be one of the drivers behind the reappearance of *Mytilus* after 1,000 years of

absence[149]. The invasion of xenobionts via rafting can have population-level or community-level effects[150], posing a potential threat to Arctic ecosystems.

Ecological effects of plastic. Because of the widespread contamination of plastic pollution in wildlife, there is urgency to answer questions related to ecological impact[150,151]. In non-Arctic systems, there is overwhelming evidence of detrimental effects from macroplastics to individuals and compelling evidence for effects to populations, communities and ecosystems[150]. For microplastics, impacts have been demonstrated across several levels of biological organization[150,152], including oxidative stress[153], changes in gene expression[136,154], inflammation[155] and reduced growth[156] and reproduction[157] rates. Although these effects could apply to closely related Arctic species, too, there has been little research on the ecological effects of plastic debris in Arctic ecosystems, which are already under stress due to climate change[158].

One of the few studies available on the effects of plastic on benthic species is in the deep Fram Strait, where 45% of the plastic debris observed showed interactions with epibenthic megafauna, such as entanglement in up to 31% of the sponge colonies[12]. Although data on effects are lacking in this case, entangled fishing gear caused tissue abrasion and (partial) mortality in sponges from Florida, rendering the organisms more susceptible to pathogens, predation and overgrowth[159]. As with cold-water coral[160], coverage of the sponge's feeding apparatus could impair water-exchange processes, prey capture and growth. Another frequent observation was the colonization of plastic debris by sessile biota such as sea anemones[12,103], which affects diversity. In general, the presence of plastic debris in benthic sediments can alter community structure[161]. Plastic items covering sediments can also affect biogeochemical processes, which could alter bottom-dwelling communities, as shown in an intertidal zone in Ireland with anoxic conditions, reduced organic matter and lower densities of sediment-inhabiting invertebrates nine weeks after coverage with plastic bags[162]. Although sediments from the Fram Strait and Canada contain up to 13,000 and 16,000 small-sized microplastics kg^{-1} sediment[58,81] and are, thus, amongst the most polluted in the world, the effects on deposit-feeding organisms such as sea cucumbers, nematodes or other worms are currently largely unknown.

Sea ice also harbours high concentrations of microplastics[29], which likely affect this ecosystem. Experimental evidence suggests that the presence of microplastic reduces the colonization of already formed sea ice by ice algae, a process that is important to transfer sea ice species from multi-year to first-year ice[90]. If added during the process of ice formation, however, microplastic did not affect algal concentrations in sea ice.

Data on contamination are often collected before digging deeper into effects. Here, we suggest that it is time for a new research priority: understanding the effects of plastics in the Arctic across organismal and ecosystem scales. These efforts are especially important, as the Arctic is vulnerable to a combination of many stressors (for instance, fast warming and a sink for organic pollutants), and the addition of microplastics raises concern about multi-stressor effects to wildlife.

Plastic pollution and climate change

Although they are often thought of separately, climate change and plastic pollution are directly and indirectly linked, and both are amongst the biggest ecological challenges faced today globally and in the Arctic (FIG. 6), not least they share the same fossil origin, oil and gas. Global heating is three times faster in the Arctic compared with the rest of the planet[23], such that Arctic ecosystems are already under severe stress[158]. One of the most prominent effects of climate change is the melting of the cryosphere. Sea ice entrains microplastic during its formation[90,163] and releases it during melting[26,29,61]. Changes in ice properties and its distribution will, therefore, affect the levels and spatial distribution of microplastics in the environment. Increasing quantities of released plastic particles in the water column, along with extracellular polymeric substances from ice algae[90], could promote the formation of heteroaggregates, affecting the nutrient availability and turbidity in habitats of cyanobacteria and phytoplankton communities[6]. A decline in their populations could reduce the sequestration of carbon from the atmosphere and, thereby, fuel climate change instead[6,164]. On a smaller scale, a positive correlation has been found between salinity and microplastic concentrations in sea ice brine[90,163]. The microplastic levels reported in Arctic sea ice could increase the albedo effect by 11% and alter both the permeability of sea ice and the absorption of solar radiation, with a feedback on sea ice melting[29,163]. However, it is also conceivable that high concentrations of particles darker than the cryosphere promote solar absorption and, thus, melting.

In the atmosphere, airborne microplastic and nanoplastic can also enhance ice nucleation and, thereby, cloud formation and climate change[165] if they contribute to atmospheric trapping of infrared radiation from the Earth surface, instead of enhancing the reflection of sunlight. This process is important for the hydrological cycle, as more than 50% of the Earth's precipitation is induced in the ice phase[165]. Through atmospheric fallout and glacial meltwater, microplastics could also penetrate and affect permafrost, and be released to rivers and the Arctic Ocean with accelerating permafrost thaw[166]. Airborne microplastics have also infiltrated snow on glaciers, potentially affecting their light absorbance, structural and general rheological properties, and could, thereby, promote the ongoing fast melting of glaciers, the greatest cause of rising sea levels[110].

Growing inputs of freshwater to the Arctic Ocean lead to a decrease in the relative buoyancy of plastics debris[167] and a weakening thermohaline circulation[168], which could eventually slow down the poleward transport of plastic pollution (FIG. 6). Global warming also amplifies poleward winds[169], which define convergence zones and surface currents and, thus, influence plastic transport, as convergence zones are accumulation areas for plastic debris[10]. Furthermore, higher wind speeds promote the vertical mixing of small plastics into deeper waters[170]. In addition, warming surface waters result in a higher frequency of storms[171], which break up the sea ice and enhance melting[172]. Sea level rise and storm events bring about higher inputs of plastic debris from land to the ocean via water runoff[173] and wind transport. Over time,
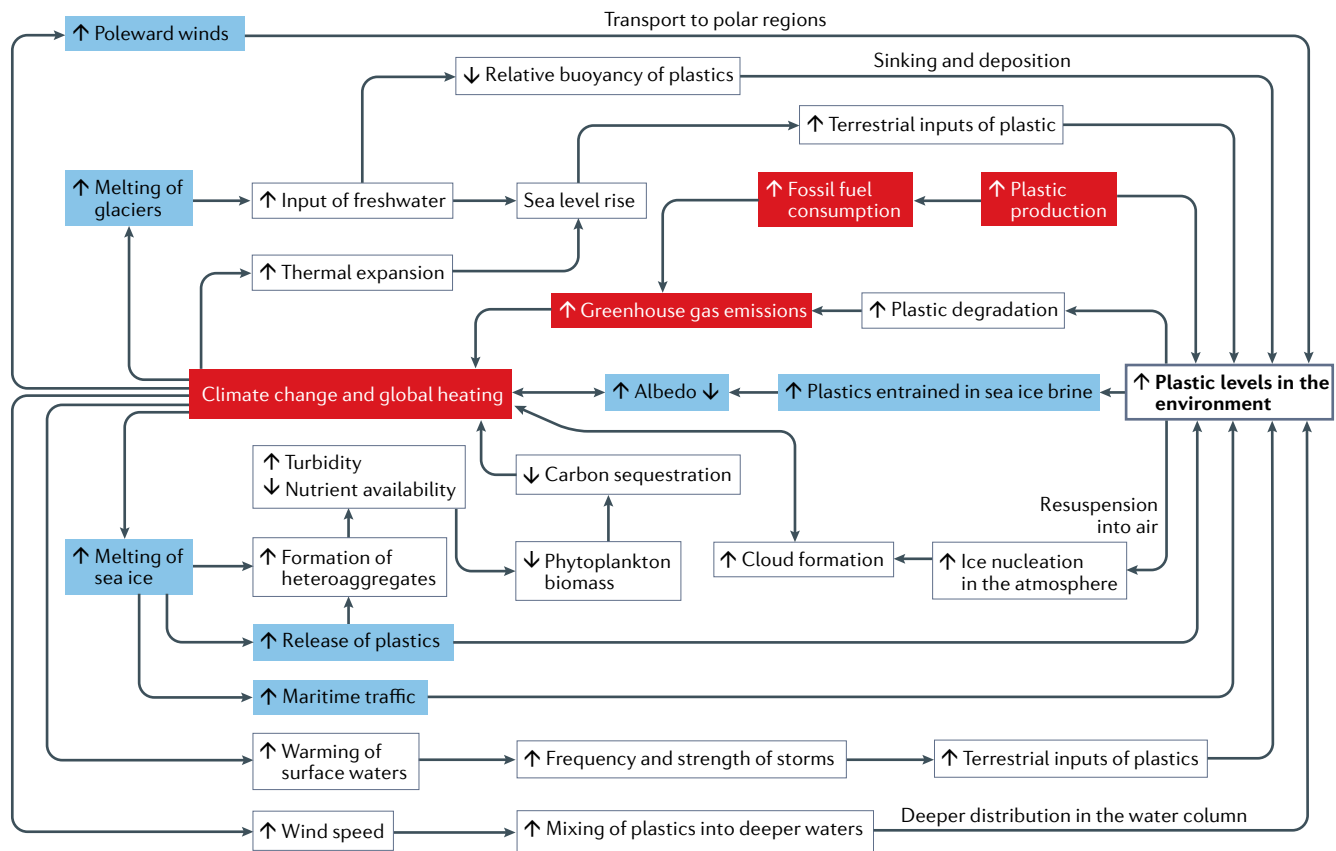
Fig. 6 | **The interaction between climate change and plastic pollution.** Climate change and plastic pollution are interconnected. Several meteorological or physical impacts of climate change are known to influence the concentrations and distribution of plastic in the world, at different scales. All of these lead to an increase in plastic concentration, at least locally. Blue boxes refer to processes specific to polar regions. This figure highlights the complexity of those interconnections and how two major anthropogenic challenges are influencing each other. Figure adapted with permission from REF.[167], Society of Environmental Toxicology and Chemistry (Wiley). © 2017 SETAC.

these processes could also lead to higher pollution levels in the Arctic Ocean[11,15,24]. In addition to direct effects, there are many indirect links between plastic pollution and climate change. For example, climate change causes a decrease in the sea ice thickness and extent[174]. As a result, maritime traffic in the Arctic is on the rise[175], leading to higher levels of plastic pollution, for example, from fishing vessels, merchant shipping or tourist activities[49].

Plastic production also fuels climate change, as it accounts for 6% of the global oil consumption and could reach 20% by 2050 (REF.[176]). Fossil-based plastics produced in 2015 emitted 1.8 gigatons of equivalent CO_2 over their life cycle[177]. Under the current trajectory, plastic-related CO_2 emissions could rise to 6.5 gigatons by 2050, which will accelerate climate change and could use up 10–13% of the remaining SR15 carbon budget of 570 gigatons to limit warming to a 66% chance of staying below 1.5 °C (REF.[178]). Furthermore, greenhouse gases such as methane, ethylene, ethane and propylene are released during degradation of some common plastic polymers throughout their lifetime[179]. Polyethylene, the most produced plastic polymer[1], releases the highest levels of methane and ethylene. Once initiated by solar radiation, such as in the surface ocean, this process continues in the dark[179]. The scale of greenhouse gas emissions from these processes are currently unknown.

Mitigation

Plastic pollution is a transboundary problem, especially in the Arctic, where it stems from both distant and local sources. The problem, thus, needs to be tackled both regionally and internationally. Plastic pollution is a function of increasing plastic production coupled with inadequate waste management. Therefore, an effective upstream reduction in the global production of plastic waste via binding targets set in international treaties similar to the Paris Agreement or Montreal Protocol[2,180] is warranted. In addition, a circular use of plastic and of sustainable and truly biodegradable alternatives are needed alongside improved municipal waste collection and management to help reduce leakage to the environment[2,180]. Manual clean-ups on shorelines, harbours and riverbanks can help to mitigate pollution if impact assessments show that benefits outweigh environmental cost[181], such as disturbance and increased mortality of biota due to incidental by-catch caused by non-selective removal technologies or operational greenhouse gas emissions.

Emissions from sea-based sources lead directly to marine pollution because of the direct input pathways. As much of the plastic debris in the Arctic region stems from local and distant commercial fisheries, mitigation in this sector would reduce plastic pollution particularly efficiently. Gear-marking schemes can prevent fishing gear

loss and discarding[182], along with incentives for adequate waste disposal[183]. Programmes for reporting and recovery of lost fishing gear are already in place in Norway and should be extended to other regions[184], as should be schemes to recycle fishing gear, which are currently practiced in Iceland. In the long run, the use of fully biodegradable material for nets[185,186], along with bans on particularly short-lived components, such as dolly ropes, that become abraded during a trawl's passage on the seafloor, could help to reduce leakage to the environment. Education awareness campaigns designed for fishers, for example, during mandatory sea survival courses, help to shift perception in the industry but must be accompanied by institutionalized and well-organized waste facilities at fish landings and harbours to foster behavioural change[184]. The disposal of plastic in the Arctic Ocean and adjacent areas could be reduced through improved port reception facilities following a regional reception facilities plan, as is currently underway under the International Maritime Organization in the Pacific region. Lower harbour fees for ships with better waste facilities on board, a 'No Special Fee' system similar to HELCOM[187] and on-port recycling hubs could help to alleviate illegal dumping of waste at sea. Given that ship traffic has already increased and will further increase in the Arctic due to vanishing sea ice, this sector deserves particular attention, including improved surveillance schemes.

In many locations throughout the Arctic, open landfills are still in use[56], and it is clear that investments in local waste management solutions will reduce the leakage of plastic pollution to the environment. Rural Arctic communities that desire efficient waste collection and management schemes need financial and logistical support, for instance, through extended producer responsibility schemes or governments to establish or improve waste management and treatment. Importantly, coupled with community-based monitoring programmes[57], sources and effectiveness of policy changes can be detected at the local scale relatively quickly[16]. Waste management studies and investments must be a priority to stem the tide of plastics from sources within the Arctic.

Reducing emissions from diffuse sources is necessary but challenging. Improved material design could reduce emissions from automotive vehicle tyres and brakes, which is one of the most important sources of microplastics globally[112], as well as from ship paint from (ice-breaking) vessels. Collection schemes of road runoff could mitigate some of the pollution as well. New regulation aimed at improvements of wastewater treatment on land, offshore and on ships could help reduce inputs of plastic microfibres.

Finally, communication and community action are needed. Global audiences must be taught about plastic pollution in the Arctic, as distant sources contribute to the plastics burden in the Arctic. It is important to include local voices in both research[46] and actions aimed at reducing plastic pollution. Listening to indigenous voices has been recognized as a critical part of communication strategies under the Arctic Council[188]. For many, plastic pollution is affecting their way of life. In northern Canada, the community focus on understanding plastic pollution in the Arctic is illustrated by the variety of community-based research programmes on litter and microplastics funded under the Northern Contaminants Program. For this reason, a course including plastic pollution as a contaminant in the Arctic has been taught at Nunavut Arctic College in Iqaluit, Canada, each year since 2009. The students learn, share stories and knowledge, and participate in local research on plastic pollution. As stated by Aggeuq Ashoona, a college student who participated in this course from Kinngait, Nunavut, "This is affecting Inuit very much […]. To find plastic in their [wildlife] stomach is heart-breaking, because these are our food".

Summary and future perspectives

Regardless of its remoteness, plastic pollution has infiltrated the Arctic from the atmosphere to the deep ocean floor, with pollution levels sufficiently high for some regions to be considered accumulation areas[15,24,81]. Despite recent advances in research, there is still a lack of understanding of the importance of different transport processes within the Arctic and the role of local sources, rivers and the atmosphere. It is clear, however, that plastic pollution exacerbates the impacts of climate change. These effects seem particularly clear in the Arctic, where not only are climate change effects occurring faster than elsewhere[23] but where these changes likely strongly influence the sources and transport of plastic debris, perhaps more so than in other regions. Still, we have barely scratched the surface when it comes to impacts on Arctic life, including human communities in the Arctic, requiring further and urgent research.

Plastic pollution research is particularly challenging in the Arctic because of its remoteness, lack of infrastructure and harsh environmental conditions. Conventional scientific sampling is often restricted to summer months and requires the use of aircraft, research bases and/or ice-class ships. Even then, fieldwork can be jeopardized by low visibility, polar bears, ice and low temperatures defying technology. Arctic landscapes are often characterized by coarse sediments, permafrost, snow and/or ice, which lack coherent survey guidelines, and, overall, these environments are currently undersampled[189]. Another common approach to quantify plastic pollution, which is to count litter floating at the sea surface by ship-based observers, is often difficult or impossible due to fog or sea ice, which can also impede sampling by surface trawls. These examples highlight that we currently lack the basic methodology to determine pollution levels in certain areas of the Arctic and during significant periods of time. In some areas, these challenges can be overcome by the use of year-round moored sampling devices[190], drones or collaborative research with citizen scientists[39,57,109,191] or local communities[192]. For example, many scientists work directly with local Inuit communities in the Canadian Arctic to design sampling schemes, sample and interpret results[46,133,193]. During the COVID-19 pandemic, many researchers in Canada could not access field sites in the Arctic, and, in some cases, local communities were compensated to undertake annual sampling. In Russia, a programme was developed to enable monitoring by local school children and students[57]. Such schemes complement professional science and should be expanded to fill knowledge gaps.

In addition to difficulties that arise while conducting fieldwork in the Arctic, there is currently a lack of standardized sampling and analytical methodologies or even harmonized procedures, especially in terms of microplastics. This lack of standardization is concerning, as different analytical approaches can cause several orders of magnitude differences in the results obtained[60,194]. Therefore, despite a surge in plastic research in the Arctic, the results are often not comparable between studies, hampering efforts to describe the sources, sinks and large-scale distribution patterns of Arctic plastic pollution. However, the research and monitoring recommendations recently set out by the Arctic Monitoring and Assessment Programme (AMAP)[17] could inform a more harmonized research approach, which would also benefit from a common database for the upload of recorded pollution data.

Nanoplastics in the Arctic have largely not been investigated, including their distribution amongst different ecosystem compartments and how they interact with microplastics as the sea ice forms and melts. It is conceivable, for example, that nanoplastic interacts with sea ice in a similar way as, for example, salt and is rejected from the ice matrix as sea ice forms. Data on nanoplastic are particularly important, as particles of this size fraction can pass biological membranes and, thus, translocate to organs, where they could elicit a strong biologic response[195]. Progress in the development of sampling and analytical methods have not only demonstrated the presence of nanoplastic in glacial ice from Greenland but will also help us to fill this knowledge gap[196].

Currently, there are no plastic budget data on relative contributions of various sources of plastic to the Arctic, such as local versus long-distance sources. Current understanding suggests that, along with local emissions, inputs of Atlantic origin could be most important, but data from the Amerasian Arctic have only begun to emerge, so no firm conclusions can yet be drawn. Information on the sources of pollution is needed to assess pan-Arctic exchange — how much plastic debris leaks from North America to Europe and vice versa. As outlined in this Review, such assessments are currently hampered by the lack of harmonized data. Another major knowledge gap pertains to atmospheric transport, which allows microplastic and nanoplastic to infiltrate even the most remote ecosystems on our planet via precipitation. Although this pathway is important for other pollutants such as mercury[111], its contribution to the Arctic's overall plastic burden is unknown. Integrating microplastic sampling into research cruises and ongoing air pollution observation programmes could improve our understanding of the role of airborne microplastics[197].

The amount of plastic debris entering the Arctic Ocean through rivers is unclear, but could be important, owing to their enormous catchment areas that lie beyond the Arctic borders, some of which pass through big cities. Arctic rivers are a conduit of land-based plastic pollution into the ocean, and their massive discharge every spring or summer makes the impact potentially substantial. With over 37 million people living along these waterways[16], understanding plastic pollution in rivers that drain into the Arctic Ocean is crucial. It also increases our knowledge of terrestrial sources, which can help mitigate its input in the long run. Especially as local people depend on freshwater and land for subsistence and culture, understanding the effects of plastic pollution in these systems is a priority. Given the interest in litter and microplastics in northern and indigenous communities, and the breadth of community-based research and monitoring projects across the Arctic, locally designed and implemented projects should be prioritized within research planning strategies[46,57]. This strategy will ensure that local and regional research needs are included, and local communities are engaged in result discussions throughout the process and can relay this information as directly into policy solutions as needed.

The propagation and impact of microplastic within the Arctic food web (FIG. 5), which is already under pressure from fast climate forcing, is another source of major uncertainty. Targeted work that examines plastic pollution throughout the food web is needed in order to understand where plastic pollution accumulates and the actual effects on biota. Although studies have focused hitherto on single species, future studies should take an ecosystem approach, with sampling of biota across trophic levels[153], and in relation to environmental compartments where they feed[17]. This knowledge will help tease apart questions relating to bioaccumulation, biomagnification, excretion and, thus, cycling of both plastic pollution and contaminants that are both sorbed and derived from plastic pollution.

We are also only beginning to investigate the effects of microplastic and nanoplastic on important physical processes, such as soil functions, biogeochemistry, ice properties (melting, UV reflectance and attenuation), weather (condensation, precipitation) and particle flux through the water column (biological pump), all of which have repercussions for the functioning of our Earth system, especially in a changing Arctic. However, it is already clear that effective mitigation is urgently needed to prevent further deterioration of Arctic ecosystems and communities.

Published online 5 April 2022

1. Plastics Europe. Plastics — the Facts 2020: An analysis of European plastics production, demand and waste data (Plastics Europe, 2020).
2. Borrelle, S. B. et al. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science* **369**, 1515–1518 (2020).
3. Brahney, J. et al. Constraining the atmospheric limb of the plastic cycle. *Proc. Natl Acad. Sci. USA* **118**, e2020719118 (2021).
4. Bergmann, M., Tekman, M. B. & Gutow, L. Marine litter: Sea change for plastic pollution. *Nature* **544**, 297–297 (2017).
5. Villarrubia-Gómez, P., Cornell, S. E. & Fabres, J. Marine plastic pollution as a planetary boundary threat—The drifting piece in the sustainability puzzle. *Mar. Policy* **96**, 213–220 (2018).
6. MacLeod, M., Arp, H. P. H., Tekman, M. B. & Jahnke, A. The global threat from plastic pollution. *Science* **373**, 61–65 (2021).
7. Gigault, J. et al. Current opinion: What is a nanoplastic? *Environ. Pollut.* **235**, 1030–1034 (2018).
8. Andrady, A. L. in *Marine Anthropogenic Litter* (eds Bergmann, M., Gutow, L. & Klages, M.) 57–72 (Springer, 2015).
9. van Sebille, E. et al. A global inventory of small floating plastic debris. *Environ. Res. Lett.* **10**, 124006 (2015).
10. Cózar, A. et al. Plastic debris in the open ocean. *Proc. Natl Acad. Sci. USA* **111**, 10239–10244 (2014).
11. van Sebille, E., England, M. H. & Froyland, G. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. *Environ. Res. Lett.* **7**, 044040 (2012).
12. Parga Martínez, K. B., Tekman, M. B. & Bergmann, M. Temporal trends in marine litter at three stations of

the HAUSGARTEN observatory in the Arctic deep sea. *Front. Mar. Sci.* **7**, 321 (2020).

13. Ostle, C. et al. The rise in ocean plastics evidenced from a 60-year time series. *Nat. Commun.* **10**, 1622 (2019).

14. Barrows, A. P. W., Cathey, S. E. & Petersen, C. W. Marine environment microfiber contamination: Global patterns and the diversity of microparticle origins. *Environ. Pollut.* **237**, 275–284 (2018).

15. Lima, A. R. A. et al. Global patterns for the spatial distribution of floating microfibers: Arctic Ocean as a potential accumulation zone. *J. Hazard. Mater.* **403**, 123796 (2021).

16. Protection of the Arctic Marine Environment (PAME). Desktop study on marine litter including microplastics in the Arctic (PAME, 2019).

17. Arctic Monitoring and Assessment Programme (AMAP). AMAP litter and microplastics monitoring guidelines. Version 1.0, 257 pp (AMAP, 2021).

18. Collard, F. & Ask, A. Plastic ingestion by Arctic fauna: A review. *Sci. Total Environ.* **786**, 147462 (2021).

19. Baak, J. et al. Plastic ingestion by seabirds in the circumpolar Arctic: a review. *Environ. Rev.* **28**, 506–516 (2020).

20. Eriksen, M. et al. Mitigation strategies to reverse the rising trend of plastics in Polar Regions. *Environ. Int.* **139**, 105704 (2020).

21. Tirelli, V., Suaria, G. & Lusher, A. L. in *Handbook of Microplastics in the Environment* (eds Rocha-Santos, T., Costa, M., & Mouneyrac, C.) 1–42 (Springer, 2020).

22. Halsband, C. & Herzke, D. Plastic litter in the European Arctic: what do we know? *Emerg. Contam.* **5**, 308–318 (2019).

23. Arctic Monitoring and Assessment Programme (AMAP). Arctic climate change update 2021: key trends and impacts. Summary for policy-makers (AMAP, 2021).

24. Cózar, A. et al. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation. *Sci. Adv.* **3**, e1600582 (2017).

25. Mu, J. et al. Microplastics abundance and characteristics in surface waters from the Northwest Pacific, the Bering Sea, and the Chukchi Sea. *Mar. Pollut. Bull.* **143**, 58–65 (2019).

26. Kim, S.-K. et al. Importance of seasonal sea ice in the western Arctic ocean to the Arctic and global microplastic budgets. *J. Hazard. Mater.* **418**, 125971 (2021).

27. Yakushev, E. et al. Microplastics distribution in the Eurasian Arctic is affected by Atlantic waters and Siberian rivers. *Commun. Earth Environ.* **2**, 23 (2021).

28. Holmes, L. A., Turner, A. & Thompson, R. C. Adsorption of trace metals to plastic resin pellets in the marine environment. *Environ. Pollut.* **160**, 42–48 (2012).

29. Peeken, I. et al. Arctic sea ice is an important temporal sink and means of transport for microplastic. *Nat. Commun.* **9**, 1505 (2018).

30. van Sebille, E. et al. The physical oceanography of the transport of floating marine debris. *Environ. Res. Lett.* **15**, 023003 (2020).

31. Gavrilo, M. Plastic pollution and seabirds in the Russian Arctic (Conservation of Arctic Flora and Fauna (CAFF), 2019).

32. Nashoug, B. F. Sources of marine litter — workshop report, Svalbard 4th–6th September 2016 (SALT, 2017).

33. Benzik, A. N., Orlov, A. M. & Novikov, M. A. Marine seabed litter in Siberian Arctic: A first attempt to assess. *Mar. Pollut. Bull.* **172**, 112836 (2021).

34. OSPAR Commission. Marine litter in the North-East Atlantic Region: assessment and priorities for response (OSPAR Commission, 2009).

35. Buhl-Mortensen, L. & Buhl-Mortensen, P. Marine litter in the Nordic Seas: Distribution composition and abundance. *Mar. Pollut. Bull.* **125**, 260–270 (2017).

36. Manville, A. M. in *Proceedings of the Second International Conference on Marine Debris* (eds Shomura, R. S. & Godfrey, M. L.) 2–7 (NOAA, 1990).

37. Polasek, L. et al. Marine debris in five national parks in Alaska. *Mar. Pollut. Bull.* **117**, 371–379 (2017).

38. Falk-Andersson, J. et al. Svalbard Beach litter deep dive (SALT, 2019).

39. Bergmann, M., Lutz, B., Tekman, M. B. & Gutow, L. Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. *Mar. Pollut. Bull.* **125**, 535–540 (2017).

40. Jaskólski, M. W., Pawłowski, Ł., Strzelecki, M. C., Zagórski, P. & Lane, T. P. Trash on Arctic beach: Coastal pollution along Calypsostranda, Bellsund, Svalbard. *Pol. Polar Res.* **39**, 211–224 (2018).

41. Węsławski, J. M. & Kotwicki, L. Macro-plastic litter, a new vector for boreal species dispersal on Svalbard. *Pol. Polar Res.* **39**, 165–174 (2018).

42. Vesman, A., Moulin, E., Egorova, A. & Zaikov, K. Marine litter pollution on the Northern Island of the Novaya Zemlya archipelago. *Mar. Pollut. Bull.* **150**, 110671 (2020).

43. Mallory, M. L. et al. Anthropogenic litter in marine waters and coastlines of Arctic Canada and West Greenland. *Sci. Total Environ.* **783**, 146971 (2021).

44. Kylin, H. Marine debris on two Arctic beaches in the Russian Far East. *Polar Res.* **39**, 3381 (2020).

45. Tošić, T. N., Vruggink, M. & Vesman, A. Microplastics quantification in surface waters of the Barents, Kara and White Seas. *Mar. Pollut. Bull.* **161**, 111745 (2020).

46. Liboiron, M. et al. Abundance and types of plastic pollution in surface waters in the Eastern Arctic (Inuit Nunangat) and the case for reconciliation science. *Sci. Total Environ.* **782**, 146809 (2021).

47. Merrell, J. & Theodore, R. in *Proceedings of the Workshop on the Fate and Impact of Marine Debris* (eds Shomura, R. S. & Yoshida, Y. O.) 26–29 (NOAA, 1984).

48. Ivanova, L., Sokolov, K. & Kharitonova, G. Plastic pollution tendencies of the Barents Sea and adjacent waters under the climate change. *Arct. North* **32**, 121–145 (2021).

49. Tekman, M. B., Krumpen, T. & Bergmann, M. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. *Deep Sea Res. I* **120**, 88–99 (2017).

50. Melia, N., Haines, K. & Hawkins, E. Sea ice decline and 21st century trans-Arctic shipping routes. *Geophys. Res. Lett.* **43**, 9720–9728 (2016).

51. Jambeck, J. R. et al. Plastic waste inputs from land into the ocean. *Science* **347**, 768–771 (2015).

52. Warren, J. A., Berner, J. E. & Curtis, T. Climate change and human health: infrastructure impacts to small remote communities in the north. *Int. J. Circumpolar Health* **64**, 487–497 (2005).

53. Kirkelund, G. M., Diez, L., Scheutz, C. & Eisted, R. in *5th International Conference on Sustainable Solid Waste Management* (European Commission, 2017).

54. Eisted, R. & Christensen, T. H. Waste management in Greenland: current situation and challenges. *Waste Manag. Res.* **29**, 1064–1070 (2011).

55. Samuelson, G. M. Water and waste management issues in the Canadian Arctic: Iqaluit, Baffin Island. *Can. Water Resour. J.* **23**, 327–338 (1998).

56. Kirkfeldt, T. S. *Marine Litter in Greenland*. Master's thesis, Aalborg Univ. (2019).

57. Ershova, A., Makeeva, I., Malgina, E., Sobolev, N. & Smolokurov, A. Combining citizen and conventional science for microplastics monitoring in the White Sea basin (Russian Arctic). *Mar. Pollut. Bull.* **173**, 112955 (2021).

58. Huntington, A. et al. A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding eastern Canadian Arctic waters of Nunavut. *FACETS* **5**, 432–454 (2020).

59. Athey, S. N. et al. The widespread environmental footprint of indigo denim microfibers from blue jeans. *Environ. Sci. Technol. Lett.* **7**, 840–847 (2020).

60. Rist, S. et al. Quantification of plankton-sized microplastics in a productive coastal Arctic marine ecosystem. *Environ. Pollut.* **266**, 115248 (2020).

61. von Friesen, L. W. et al. Summer sea ice melt and wastewater are important local sources of microlitter to Svalbard waters. *Environ. Int.* **139**, 105511 (2020).

62. Granberg, M. E., Ask, A. & Gabrielsen, G. W. Local contamination in Svalbard-Overview and suggestions for remediation actions (Norwegian Polar Institute, 2017).

63. De Falco, F. et al. Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. *Environ. Pollut.* **236**, 916–925 (2017).

64. Magnusson, K. et al. Microlitter in sewage treatment systems: A Nordic perspective on waste water treatment plants as pathways for microscopic anthropogenic particles to marine systems (Nordisk Ministerråd, 2016).

65. Dippo, B. *Microplastics in the Coastal Environment of West Iceland*. Master's thesis, Univ. Akureyri (2012).

66. Granberg, M. et al. Anthropogenic microlitter in wastewater and marine samples from Ny-Ålesund, Barentsburg and Signehamna, Svalbard (IVL Swedish Environmental Research Institute, 2019).

67. United Nation Environment Programme (UNEP). Marine plastic debris and microplastics: Global lessons and research to inspire action and guide policy change (UNEP, 2016).

68. Hamilton, B. M. et al. Microplastics around an Arctic seabird colony: Particle community composition varies across environmental matrices. *Sci. Total Environ.* **773**, 145536 (2021).

69. Knutsen, H. et al. Microplastic accumulation by tube-dwelling, suspension feeding polychaetes from the sediment surface: A case study from the Norwegian Continental Shelf. *Mar. Environ. Res.* **161**, 105073 (2020).

70. Bergmann, M., Sandhop, N., Schewe, I. & D'Hert, D. Observations of floating anthropogenic litter in the Barents Sea and Fram Strait, Arctic. *Polar Biol.* **39**, 553–560 (2016).

71. Lusher, A. L., Tirelli, V., O'Connor, I. & Officer, R. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. *Sci. Rep.* **5**, 14947 (2015).

72. Pogojeva, M. et al. Distribution of floating marine macro-litter in relation to oceanographic characteristics in the Russian Arctic Seas. *Mar. Pollut. Bull.* **166**, 112201 (2021).

73. Mountford, A. S. & Morales Maqueda, M. A. Modeling the accumulation and transport of microplastics by sea ice. *J. Geophys. Res.* **126**, e2020JC016826 (2021).

74. Onink, V., Wichmann, D., Delandmeter, P. & van Sebille, E. The role of Ekman currents, geostrophy, and Stokes drift in the accumulation of floating microplastic. *J. Geophys. Res.* **124**, 1474–1490 (2019).

75. Chia-Ying, K., Yi-Chia, H. & Ming-Shiou, J. Global distribution and cleanup opportunities for macro ocean litter: A quarter century of accumulation dynamics under windage effects. *Environ. Res. Lett.* **15**, 104063 (2020).

76. Thiel, M., Hinojosa, I. A., Joschko, T. & Gutow, L. Spatio-temporal distribution of floating objects in the German Bight (North Sea). *J. Sea Res.* **65**, 368–379 (2011).

77. Brach, L. et al. Anticyclonic eddies increase accumulation of microplastic in the North Atlantic subtropical gyre. *Mar. Pollut. Bull.* **126**, 191–196 (2018).

78. Pan, Z. et al. Microplastics in the Northwestern Pacific: Abundance, distribution, and characteristics. *Sci. Total Environ.* **650**, 1913–1922 (2019).

79. Pnyushkov, A., Polyakov, I. V., Padman, L. & Nguyen, A. T. Structure and dynamics of mesoscale eddies over the Laptev Sea continental slope in the Arctic Ocean. *Ocean Sci.* **14**, 1329–1347 (2018).

80. Wekerle, C. et al. Eddy-resolving simulation of the Atlantic water circulation in the Fram Strait with focus on the seasonal cycle. *J. Geophys. Res.* **122**, 8385–8405 (2017).

81. Tekman, M. B. et al. Tying up loose ends of microplastic pollution in the Arctic: Distribution from the sea surface, through the water column to deep-sea sediments at the HAUSGARTEN observatory. *Environ. Sci. Technol.* **54**, 4079–4090 (2020).

82. Wichmann, D., Delandmeter, P. & van Sebille, E. Influence of near-surface currents on the global dispersal of marine microplastic. *J. Geophys. Res.* **124**, 6086–6096 (2019).

83. Kühn, S., Bravo Rebolledo, E. L. & van Franeker, J. A. in *Marine Anthropogenic Litter* (eds Bergmann, M., Gutow, L. & Klages, M.) 75–116 (Springer, 2015).

84. LITTERBASE. Online Portal for Marine Litter. www.litterbase.org (2021).

85. Kanhai, L. D. K. et al. Microplastics in sub-surface waters of the Arctic Central Basin. *Mar. Pollut. Bull.* **130**, 8–18 (2018).

86. Ross, P. S. et al. Pervasive distribution of polyester fibres in the Arctic Ocean is driven by Atlantic inputs. *Nat. Commun.* **12**, 106 (2021).

87. Obbard, R. W. et al. Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earths Future* **2**, EF000240 (2014).

88. Kanhai, L. D. K., Gardfeldt, K., Krumpen, T., Thompson, R. C. & O'Connor, I. Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. *Sci. Rep.* **10**, 5004 (2020).

89. Juhl, A. R., Krembs, C. & Meiners, K. M. Seasonal development and differential retention of ice algae and other organic fractions in first-year Arctic sea ice. *Mar. Ecol. Prog. Ser.* **436**, 1–16 (2011).

90. Hoffmann, L., Eggers, S. L., Allhusen, E., Katlein, C. & Peeken, I. Interactions between the ice algae *Fragillariopsis cylindrus* and microplastics in sea ice. *Environ. Int.* **139**, 105697 (2020).

91. Wollenburg, J. E. et al. Ballasting by cryogenic gypsum enhances carbon export in a *Phaeocystis* under-ice bloom. *Sci. Rep.* **8**, 7703 (2018).

92. Bergmann, M. et al. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. *Environ. Sci. Technol.* **51**, 11000–11010 (2017).

93. Frank, Y. A. et al. Preliminary screening for microplastic concentrations in the surface water of the Ob and Tom Rivers in Siberia, Russia. *Sustainability* **13**, 80 (2021).

94. Engler, R. E. The complex interaction between marine debris and toxic chemicals in the ocean. *Environ. Sci. Technol.* **46**, 12302–12315 (2012).

95. Grøsvik, B. E. et al. Assessment of marine litter in the Barents Sea, a part of the Joint Norwegian–Russian Ecosystem Survey. *Front. Mar. Sci.* **5**, 72 (2018).

96. Coyle, R., Hardiman, G. & Driscoll, K. O. Microplastics in the marine environment: A review of their sources, distribution processes, uptake and exchange in ecosystems. *Case Stud. Chem. Environ. Eng.* **2**, 100010 (2020).

97. Brunner, K., Kukulka, T., Proskurowski, G. & Law, K. L. Passive buoyant tracers in the ocean surface boundary layer: 2. Observations and simulations of microplastic marine debris. *J. Geophys. Res. Oceans* **120**, 7559–7573 (2015).

98. Wobus, F., Shapiro, G. I., Huthnance, J. M. & Maqueda, M. A. M. The piercing of the Atlantic Layer by an Arctic shelf water cascade in an idealised study inspired by the Storfjorden overflow in Svalbard. *Ocean Model.* **71**, 54–65 (2013).

99. Buhl-Mortensen, P., Gordon, D. C., Buhl-Mortensen, L. & Kulka, D. W. First description of a *Lophelia pertusa* reef complex in Atlantic Canada. *Deep Sea Res. I* **126**, 21–30 (2017).

100. Purser, A. et al. Local variation in the distribution of benthic megafauna species associated with cold-water coral reefs on the Norwegian margin. *Cont. Shelf Res.* **54**, 37–51 (2013).

101. Sen, A. et al. Atypical biological features of a new cold seep site on the Lofoten-Vesterålen continental margin (northern Norway). *Sci. Rep.* **9**, 1762 (2019).

102. Woodall, L. C. et al. The deep sea is a major sink for microplastic debris. *R. Soc. Open Sci.* **1**, 140317 (2014).

103. Schulz, M., Bergmann, M., von Juterzenka, K. & Soltwedel, T. Colonisation of hard substrata along a channel system in the deep Greenland Sea. *Polar Biol.* **33**, 1359–1369 (2010).

104. Kanhai, L. D. K. et al. Deep sea sediments of the Arctic Central Basin: A potential sink for microplastics. *Deep Sea Res. I* **145**, 137–142 (2019).

105. Mu, J. et al. Abundance and distribution of microplastics in the surface sediments from the northern Bering and Chukchi Seas. *Environ. Pollut.* **245**, 122–130 (2019).

106. Kuroda, M. et al. The current state of marine debris on the seafloor in offshore area around Japan. *Mar. Pollut. Bull.* **161**, 111670 (2020).

107. Kane, I. A. et al. Seafloor microplastic hotspots controlled by deep-sea circulation. *Science* **368**, 1140–1145 (2020).

108. Collard, F. et al. Anthropogenic particles in sediment from an Arctic fjord. *Sci. Total Environ.* **772**, 145575 (2021).

109. Bergmann, M. et al. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. *Sci. Adv.* **5**, eaax1157 (2019).

110. Stefánsson, H. et al. Microplastics in glaciers: first results from the Vatnajökull ice cap. *Sustainability* **13**, 4183 (2021).

111. Outridge, P. M., Macdonald, R. W., Wang, F., Stern, G. A. & Dastoor, A. P. A mass balance inventory of mercury in the Arctic Ocean. *Environ. Chem.* **5**, 89–111 (2008).

112. Evangeliou, N. et al. Atmospheric transport is a major pathway of microplastics to remote regions. *Nat. Commun.* **11**, 3381 (2020).

113. Allen, S. et al. Examination of the ocean as a source for atmospheric microplastics. *PLoS One* **15**, e0232746 (2020).

114. Iversen, M. et al. The diet of polar bears (*Ursus maritimus*) from Svalbard, Norway, inferred from scat analysis. *Polar Biol.* **36**, 561–571 (2013).

115. Botterell, Z. L. R. et al. Microplastic ingestion in zooplankton from the Fram Strait in the Arctic. *Sci. Total Environ.* (in the press).

116. Fang, C. et al. Microplastics in three typical benthic species from the Arctic: Occurrence, characteristics, sources, and environmental implications. *Environ. Res.* **192**, 110326 (2021).

117. Fang, C. et al. Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions. *Chemosphere* **209**, 298–306 (2018).

118. Lusher, A., Bråte, I. L., Hurley, R., Iversen, K. & Olsen, M. Testing of methodology for measuring microplastics in blue mussels (*Mytilus* spp) and sediments, and recommendations for future monitoring of microplastics (R & D-project). *Norwegian Institute for Water Research* https://niva.brage.unit.no/niva-xmlui/handle/11250/2470297 (2017).

119. Iannilli, V., Pasquali, V., Setini, A. & Corami, F. First evidence of microplastics ingestion in benthic amphipods from Svalbard. *Environ. Res.* **179**, 108811 (2019).

120. Morgana, S. et al. Microplastics in the Arctic: a case study with sub-surface water and fish samples off Northeast Greenland. *Environ. Pollut.* **242**, 1078–1086 (2018).

121. de Vries, A. N., Govoni, D., Ärnason, S. H. & Carlsson, P. Microplastic ingestion by fish: Body size, condition factor and gut fullness are not related to the amount of plastics consumed. *Mar. Pollut. Bull.* **151**, 110827 (2020).

122. Kühn, S. et al. Plastic ingestion by juvenile polar cod (*Boreogadus saida*) in the Arctic Ocean. *Polar Biol.* **41**, 1269–1278 (2018).

123. Bråte, I. L. N., Eidsvoll, D. P., Steindal, C. C. & Thomas, K. V. Plastic ingestion by Atlantic cod (*Gadus morhua*) from the Norwegian coast. *Mar. Pollut. Bull.* **112**, 105–110 (2016).

124. Liboiron, M. et al. Low incidence of plastic ingestion among three fish species significant for human consumption on the island of Newfoundland, Canada. *Mar. Pollut. Bull.* **141**, 244–248 (2019).

125. Nielsen, J., Hedeholm, R. B., Simon, M. & Steffensen, J. F. Distribution and feeding ecology of the Greenland shark (*Somniosus microcephalus*) in Greenland waters. *Polar Biol.* **37**, 37–46 (2014).

126. Leclerc, L.-M. et al. A missing piece in the Arctic food web puzzle? Stomach contents of Greenland sharks sampled in Svalbard, Norway. *Polar Biol.* **35**, 1197–1208 (2012).

127. Trevail, A. M., Gabrielsen, G. W., Kühn, S., & Van Franeker, J. A. Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (*Fulmarus glacialis*). *Polar Biol.* **38**, 975–981 (2015).

128. Provencher, J. F. et al. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. *Anal. Methods* **9**, 1454–1469 (2017).

129. Martin, A. R. & Clarke, M. R. The diet of sperm whales (*Physeter macrocephalus*) captured between Iceland and Greenland. *J. Mar. Biol. Assoc. UK* **66**, 779–790 (2009).

130. Moore, R. C. et al. Microplastics in beluga whales (*Delphinapterus leucas*) from the Eastern Beaufort Sea. *Mar. Pollut. Bull.* **150**, 110723 (2020).

131. Finley, K. J. Natural history and conservation of the Greenland whale, or bowhead, in the Northwest Atlantic. *Arctic* **54**, 55–76 (2001).

132. Walker, W. A. & Hanson, M. B. Biological observations on Stejneger's beaked whale, *Mesoplodon Stejnegeri*, from strandings on Adak Island, Alaska. *Mar. Mamm. Sci.* **15**, 1314–1329 (1999).

133. Bourdages, M. P. T. et al. No plastics detected in seal (Phocidae) stomachs harvested in the eastern Canadian Arctic. *Mar. Pollut. Bull.* **150**, 110772 (2020).

134. Pinzone, M. et al. First record of plastic debris in the stomach of a hooded seal pup from the Greenland Sea. *Mar. Pollut. Bull.* **167**, 112350 (2021).

135. Carlsson, P., Singdahl-Larsen, C. & Lusher, A. L. Understanding the occurrence and fate of microplastics in coastal Arctic ecosystems: The case of surface waters, sediments and walrus (*Odobenus rosmarus*). *Sci. Total Environ.* **792**, 148308 (2021).

136. Rochman, C. M., Manzano, C., Hentschel, B. T., Simonich, S. L. M. & Hoh, E. Polystyrene plastic: a source and sink for polycyclic aromatic hydrocarbons in the marine environment. *Environ. Sci. Technol.* **47**, 13976–13984 (2013).

137. Lavers, J. L. & Bond, A. L. Ingested plastic as a route for trace metals in Laysan Albatross (*Phoebastria immutabilis*) and Bonin Petrel (*Pterodroma hypoleuca*) from Midway Atoll. *Mar. Pollut. Bull.* **110**, 493–500 (2016).

138. Herzke, D. et al. Negligible impact of ingested microplastics on tissue concentrations of persistent organic pollutants in northern fulmars off coastal Norway. *Environ. Sci. Technol.* **50**, 1924–1933 (2015).

139. Provencher, J. F., Ammendolia, J., Rochman, C. M. & Mallory, M. L. Assessing plastic debris in aquatic food webs: what we know and don't know about uptake and trophic transfer. *Environ. Rev.* **27**, 304–317 (2018).

140. Neumann, S. et al. Ingested plastics in northern fulmars (*Fulmarus glacialis*): A pathway for polybrominated diphenyl ether (PBDE) exposure? *Sci. Total Environ.* **778**, 146313 (2021).

141. AMAP assessment 2016: chemicals of emerging Arctic concern (Arctic Monitoring and Assessment Programme (AMAP), 2017).

142. Lu, Z. et al. Occurrence of substituted diphenylamine antioxidants and benzotriazole UV stabilizers in Arctic seabirds and seals. *Sci. Total Environ.* **663**, 950–957 (2019).

143. Padula, V., Beaudreau, A. H., Hagedorn, B. & Causey, D. Plastic-derived contaminants in Aleutian Archipelago seabirds with varied foraging strategies. *Mar. Pollut. Bull.* **158**, 111435 (2020).

144. Bech, G. Retrieval of lost gillnets at Ilulissat Kangia (Northwest Atlantic Fisheries Organization (NAFO), 1995).

145. Kapel, F. O. A note on the net-entanglement of a bowhead whale (*Balaena mysticetus*) in Northwest Greenland, November 1980. Report of the International Whaling Commission, 35, 377–378 (1985).

146. Aasen, A. et al. Survey report from the joint Norwegian/Russian Ecosystem Survey in the Barents Sea and adjacent waters, August-October 2013 (IMR/PINRO, 2013).

147. Prokhorova, T. in *Survey Report from the Joint Norwegian/Russian Ecosystem Survey in the Barents Sea and Adjacent Waters, August-October 2014* Vol. 1/2015 (ed Eriksen, E.) 1–153 (IMR/PINRO, 2014).

148. Barnes, D. K. A. & Milner, P. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Mar. Biol.* **146**, 815–825 (2005).

149. Kotwicki, L. et al. The re-appearance of the *Mytilus* spp. complex in Svalbard, Arctic, during the Holocene: The case for an arrival by anthropogenic flotsam. *Glob. Planet. Change* **202**, 103502 (2021).

150. Bucci, K., Tulio, M. & Rochman, C. M. What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecol. Appl.* **30**, e02044 (2020).

151. Galloway, T. & Lewis, C. Marine microplastics. *Curr. Biol.* **27**, R445–R446 (2017).

152. Rochman, C. M. et al. The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. *Ecology* **97**, 302–312 (2016).

153. Browne, M. A., Niven, S. J., Galloway, T. S., Rowland, S. J. & Thompson, R. C. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. *Curr. Biol.* **23**, 2388–2392 (2013).

154. Rochman, C. M., Kurobe, T., Flores, I. & Teh, S. J. Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment. *Sci. Total Environ.* **493**, 656–661 (2014).

155. von Moos, N., Burkhardt-Holm, P. & Köhler, A. Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. *Environ. Sci. Technol.* **46**, 11327–11335 (2012).

156. Kaposi, K. L., Mos, B., Kelaher, B. P. & Dworjanyn, S. A. Ingestion of microplastic has limited impact on a marine larva. *Environ. Sci. Technol.* **48**, 1638–1645 (2014).

157. Sussarellu, R. et al. Oyster reproduction is affected by exposure to polystyrene microplastics. *Proc. Natl Acad. Sci. USA.* **113**, 2430–2435 (2016).

158. Lannuzel, D. et al. The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems. *Nat. Clim. Change* **10**, 983–992 (2020).

159. Chiappone, M., Dienes, H., Swanson, D. W. & Miller, S. L. Impacts of lost fishing gear on coral reef sessile invertebrates in the Florida Keys National Marine Sanctuary. *Biol. Conserv.* **121**, 221–230 (2005).

160. Mouchi, V. et al. Long-term aquaria study suggests species-specific responses of two cold-water corals to macro-and microplastics exposure. *Environ. Pollut.* **253**, 322–329 (2019).

161. Uhrin, A. V. & Schellinger, J. Marine debris impacts to a tidal fringing-marsh in North Carolina. *Mar. Pollut. Bull.* **62**, 2605–2610 (2011).

162. Green, D. S., Boots, B., Blockley, D. J., Rocha, C. & Thompson, R. C. Impacts of discarded plastic bags on marine assemblages and ecosystem functioning. *Environ. Sci. Technol.* **49**, 5380–5389 (2015).

163. Geilfus, N. X. et al. Distribution and impacts of microplastic incorporation within sea ice. *Mar. Pollut. Bull.* **145**, 463–473 (2019).

164. Shen, M. et al. Can microplastics pose a threat to ocean carbon sequestration? *Mar. Pollut. Bull.* **150**, 110712 (2020).

165. Ganguly, M. & Ariya, P. A. Ice nucleation of model nanoplastics and microplastics: a novel synthetic protocol and the influence of particle capping at diverse atmospheric environments. *ACS Earth Space Chem.* **3**, 1729–1739 (2019).

166. Chen, X., Huang, G., Gao, S. & Wu, Y. Effects of permafrost degradation on global microplastic cycling under climate change. *J. Environ. Chem. Eng.* **9**, 106000 (2021).

167. Welden, N. A. C. & Lusher, A. L. Impacts of changing ocean circulation on the distribution of marine microplastic litter. *Integr. Environ. Assess. Manag.* **13**, 483–487 (2017).

168. Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N. & Rahmstorf, S. Current Atlantic meridional overturning circulation weakest in last millennium. *Nat. Geosci.* **14**, 118–120 (2021).

169. Alkama, R. et al. Wind amplifies the polar sea ice retreat. *Environ. Res. Lett.* **15**, 124022 (2020).

170. Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D. W. & Law, K. L. The effect of wind mixing on the vertical distribution of buoyant plastic debris. *Geophys. Res. Lett.* **39**, L07601 (2012).

171. Collins, M. et al. in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds Pörtner, H.-O. et al.) 589–655 (Intergovernmental Panel on Climate Change (IPCC), 2019).

172. Peng, L. et al. Role of intense Arctic storm in accelerating summer sea ice melt: An in situ observational study. *Geophys. Res. Lett.* **48**, e2021GL092714 (2021).

173. Werbowski, L. M. et al. Urban stormwater runoff: A major pathway for anthropogenic particles, black rubbery fragments, and other types of microplastics to urban receiving waters. *ACS ES&T Water* **1**, 1420–1428 (2021).

174. Serreze, M. C. & Meier, W. N. The Arctic's sea ice cover: trends, variability, predictability, and comparisons to the Antarctic. *Ann. N. Y. Acad. Sci.* **1436**, 36–53 (2019).

175. Mjelde, A., Martinsen, K., Eide, M. & Endresen, Ø. Environmental accounting for Arctic shipping–A framework building on ship tracking data from satellites. *Mar. Pollut. Bull.* **87**, 22–28 (2014).

176. The New Plastics Economy: Rethinking the future of plastics (World Economic Forum, 2016).

177. Zheng, J. & Suh, S. Strategies to reduce the global carbon footprint of plastics. *Nat. Clim. Change* **9**, 374–378 (2019).

178. Hamilton, L. A. & Feit, S. Plastic and climate: the hidden costs of a plastic planet (eds Kistler, A. & Muffet, C.) 1–95 (Center for International Environmental Law (CIEL), 2019).

179. Royer, S.-J., Ferrón, S., Wilson, S. T. & Karl, D. M. Production of methane and ethylene from plastic in the environment. *PLoS One* **13**, e0200574 (2018).

180. Lau, W. W. Y. et al. Evaluating scenarios toward zero plastic pollution. *Science* **369**, 1455–1461 (2020).

181. Falk-Andersson, J., Larsen Haarr, M. & Havas, V. Basic principles for development and implementation of plastic clean-up technologies: What can we learn from fisheries management? *Sci. Total Environ.* **745**, 141117 (2020).

182. He, P. & Suuronen, P. Technologies for the marking of fishing gear to identify gear components entangled on marine animals and to reduce abandoned, lost or otherwise discarded fishing gear. *Mar. Pollut. Bull.* **129**, 253–261 (2018).

183. Chen, C.-L. & Liu, T.-K. Fill the gap: Developing management strategies to control garbage pollution from fishing vessels. *Mar. Policy* **40**, 34–40 (2013).

184. Olsen, J., Nogueira, L. A., Normann, A. K., Vangelsten, B. V. & Bay-Larsen, I. Marine litter: Institutionalization of attitudes and practices among fishers in Northern Norway. *Mar. Policy* **121**, 104211 (2020).

185. Bilkovic, D. M., Havens, K. J., Stanhope, D. M. & Angstadt, K. T. Use of fully biodegradable panels to reduce derelict pot threats to marine fauna. *Conserv. Biol.* **26**, 957–966 (2012).

186. Grimaldo, E. et al. The effect of long-term use on the catch efficiency of biodegradable gillnets. *Mar. Pollut. Bull.* **161**, 111823 (2020).

187. Newman, S., Watkins, E., Farmer, A., ten Brink, P. & Schweitzer, J.-P. in *Marine Anthropogenic Litter* (eds Bergmann, M., Gutow, L. & Klages, M.) 367–394 (Springer, 2015).

188. Skimming the surface: using seabirds to monitor plastic in the Arctic (Conservation of Arctic Flora and Fauna, 2020).

189. Melvin, J., Bury, M., Ammendolia, J., Mather, C. & Liboiron, M. Critical gaps in shoreline plastics pollution research. *Front. Mar. Sci.* **8**, 845 (2021).

190. Soltwedel, T. et al. Natural variability or anthropogenically-induced variation? Insights from 15 years of multidisciplinary observations at the arctic marine LTER site HAUSGARTEN. *Ecol. Indic.* **65**, 89–102 (2016).

191. Aliani, S., Casagrande, G., Catapano, P. & Catapano, V. in *Mare Plasticum-The Plastic Sea: Combatting Plastic Pollution Through Science and* Art (eds Streit-Bianchi, M., Cimadevila, M. & Trettnak, W.) 89–116 (Springer, 2020).

192. Lennert, A. E. What happens when the ice melts? Belugas, contaminants, ecosystems and human communities in the complexity of global change. *Mar. Pollut. Bull.* **107**, 7–14 (2016).

193. Houde, M. et al. Spatial and temporal trends of alternative flame retardants and polybrominated diphenyl ethers in ringed seals (*Phoca hispida*) across the Canadian Arctic. *Environ. Pollut.* **223**, 266–276 (2017).

194. Primpke, S. et al. Critical assessment of analytical methods for the harmonized and cost-efficient analysis of microplastics. *Appl. Spectrosc.* **74**, 1012–1047 (2020).

195. Shen, M. et al. Recent advances in toxicological research of nanoplastics in the environment: A review. *Environ. Pollut.* **252**, 511–521 (2019).

196. Materić, D. et al. Nanoplastics measurements in Northern and Southern polar ice. *Environ. Res.* **208**, 112741 (2022).

197. Allen, D. et al. Micro- and nanoplastics in the marine–atmosphere environment. *Nat. Rev. Earth Environ.* https://doi.org/10.1038/s43017-022-00292-x (2022).

198. Macdonald, R. W., Harner, T. & Fyfe, J. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. *Sci. Total Environ.* **342**, 5–86 (2005).

Author contributions
M.B. conceived and led the Review and contributed with text and figures, as did F.C., J.F.P. and M.B.T. C.M.R., J.F., E.v.S. and G.W.G. contributed to the writing and editing.

Competing interests
The authors declare no competing interests.

Peer review information
Nature Reviews Earth & Environment thanks La Daana Kanhai, Miguel Morales Maqueda and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Publisher's note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Supplementary information
The online version contains supplementary material available at https://doi.org/10.1038/s43017-022-00279-8.