Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Future monitoring of litter and microplastics in the Arctic – challenges, opportunities and strategies

Jennifer F. Provencher[1*], Stefano Aliani[2], Melanie Bergmann[3], Madelaine Bourdages[4], Lene Buhl-Mortensen[5], Francois Galgani[6], Alessio Gomiero[7], Maria Granberg[8], Bjørn Einar Grøsvik[5], Bonnie M. Hamilton[9], Tanja Kögel[5,10], Jan Rene Larsen[11], Amy L. Lusher[10,12], Mark L. Mallory[13], Peter Murphy[14], Ilka Peeken[15], Sebastian Primpke[16], Jakob Strand[17], Katrin Vorkamp[18]

[1] Environment and Climate Change Canada, Ottawa, Canada
[2] National Research Council, Institute of Marine Sciences, La Spezia, Italy
[3] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, HGF-MGP Group for Deep-Sea Ecology and Technology, Bremerhaven, Germany
[4] Carlton University, Department of Geography and Environmental Studies, Ottawa, Canada
[5] Institute of Marine Research, Bergen, Norway
[6] Institut Français de Recherche et Exploitation des Mers (IFREMER), Plouzané, France
[7] Norwegian Research Centre AS (NORCE), Randaberg, Norway
[8] IVL Swedish Environmental Research Institute, Kristineberg Marine Research Station, Kristineberg, Sweden.
[9] University of Toronto, Department of Ecology and Evolutionary Biology, Toronto, Canada
[10] University of Bergen, Department of Biological Sciences, Bergen, Norway
[11] Arctic Monitoring and Assessment Programme (AMAP) Secretariat, Tromsø, Norway
[12] Norwegian Institute for Water Research (NIVA), Oslo, Norway
[13] Acadia University, Biology Department, Wolfville, Canada
[14] National Oceanic and Atmospheric Administration (NOAA)
[15] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Polar Biological Oceanography Section, Bremerhaven, Germany
[16] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Biologische Anstalt Helgoland, Helgoland, Germany
[17] Aarhus University, Department of Ecoscience, Roskilde, Denmark
[18] Aarhus University, Department of Environmental Science, Roskilde, Denmark

---

[*] Corresponding author. E-mail: Jennifer.Provencher@ec.gc.ca

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.
Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

Abstract

The Arctic Monitoring and Assessment Programme (AMAP) has published a plan and guidelines for the monitoring of litter and microplastics (MP) in the Arctic. Here we look beyond suggestions for immediate monitoring and discuss challenges, opportunities and future strategies in the long-term monitoring of litter and MP in the Arctic. Challenges are related to environmental conditions, lack of harmonization and standardization of measurements, and long-term coordinated and harmonized data storage. Furthermore, major knowledge gaps exist with regard to benchmark levels, transport, sources and effects, which should be considered in future monitoring strategies. Their development could build on the existing infrastructure and networks established in other monitoring initiatives in the Arctic, while taking into account specific requirements for litter and MP monitoring. Knowledge existing in northern and Indigenous communities, as well as their research priorities, should be integrated into collaborative approaches. The monitoring plan for litter and MP in the Arctic allows for an ecosystem-based approach, which will improve the understanding of linkages between environmental media of the Arctic, as well as links to the global problem of litter and MP pollution.

Keywords

Ecosystem, effects, Indigenous communities, sources, transport pathways

Introduction

Environmental pollution with litter, in particular plastics, is of increasing concern worldwide (UNEP, 2014). As early as the 1970s, plastic litter was reported as a problem in the marine environment (Carpenter et al., 1972). Today, environmental pollution with litter and microplastics (MP), accounting for particles with a diameter < 5 mm (GESAMP, 2016), is observed across all oceans as well as in terrestrial, freshwater and atmospheric environments, including remote regions such as the Arctic. Litter and MP can enter the Arctic environment through local sources and pathways such as landfills, shipping, tourism, fisheries and wastewater discharges (PAME, 2019), but litter and MP also reaches the Arctic from distant areas *via* transport by ocean currents, air, sea ice, or biota (Cózar et al., 2014; Obbard et al., 2014). Consequently, plastic and other items have been found across the Arctic environment (Halsband and Herzke, 2019; Tirelli et al., 2020; Collard and Ask, 2021; Mishra et al., 2021), including on beaches and shorelines (e.g. Bergmann et al., 2017a; Polasek et al., 2017; Strand et al., 2021), in snow (e.g. Bergmann et al., 2019), in water (e.g. Lusher et al., 2015; von Friesen et al., 2020), in sediments/seabeds (e.g. Bergmann et al., 2017b; Buhl-Mortensen and Buhl-Mortensen, 2017), in sea ice (e.g. Peeken et al., 2018), as well as in Arctic biota (e.g. Baak et al., 2020; Granberg et al., 2020).

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Concerns about litter and MP in the environment have been raised at both global and regional levels, including the Arctic. The *Fairbanks Declaration* issued by the Arctic Council in 2017 notes "with concern the increasing accumulation of marine debris in the Arctic, its effects on the environment and its impacts on Arctic communities" and decides "to assess the scope of the problem and contribute to its prevention and reduction, and also to continue efforts to address growing concerns relating to the increasing levels of microplastics in the Arctic and potential effects on ecosystems and human health." (p.6; Arctic Council, 2017).

The issue of litter and MP pollution in the Arctic has recently been addressed by several Working Groups of the Arctic Council (Figure 1). For example, the Working Group for the Conservation of Arctic Flora and Fauna (CAFF) addressed the plastic ingestion by seabirds in the Arctic Migratory Birds Initiative (AMBI) (CAFF, 2021a; 2021b). The Working Group for the Protection of the Arctic Marine Environment (PAME) prepared a Desktop Study on Marine Litter including Microplastics in the Arctic (PAME, 2019) and then developed a Regional Action Plan on Marine Litter in the Arctic (PAME, 2021). It includes 59 actions under eight main themes, ranging from the reduction of marine litter inputs from fisheries and aquaculture to international cooperation. It also addresses the importance of long-term harmonized monitoring of marine litter for the implementation of the Regional Action Plan, but also for the establishment of spatial and temporal trends. The monitoring of both litter and MP has been the subject of a Monitoring Plan and Monitoring Guidelines recently developed by the Arctic Monitoring and Assessment Programme (AMAP) (AMAP, 2021a; 2021b; Provencher et al., this issue). The prioritized environmental compartments for monitoring include beaches and shorelines (for litter monitoring), seabird stomachs (for monitoring of smaller particles, including MP), water and sediments (both for monitoring of MP) (AMAP, 2021b; Provencher et al., this issue). These have been prioritized for baseline and temporal trend monitoring generating data for future circumpolar assessments of levels and trends of litter and MP.

Besides this focused recommendation, the AMAP documents address multiple aspects of future monitoring of litter and MP in the Arctic that warrant further discussion and development (AMAP 2021a; b). These include, but are not limited to: 1) challenges that need to be overcome in terms of logistics, data availability and comparability; 2) opportunities regarding synergies with existing initiatives, the involvement of local communities and expansions to other monitoring media, and 3) future priorities and strategies, such as international collaboration and additional focus areas in the monitoring programmes (Figure 2). The objective of this article is to describe and discuss these aspects to elucidate relevant

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.
Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

components in the future monitoring of litter and MP in the Arctic that require continued efforts and coordination.

Challenges

The Arctic Environment

The remoteness and the climate of the Arctic pose several challenges to the establishment of a monitoring programme for litter and MP at the pan-Arctic scale. These challenges include logistic aspects, such as regular access to monitoring sites, transport of equipment and its operation under extreme environmental conditions, but also financial ones, such as balancing the high costs of running a monitoring programme for litter and MP in the Arctic against other priorities in the environmental and other sectors (Mallory et al., 2018). These circumstances underline the value in connecting with existing monitoring programmes in the Arctic, such as those for contaminants (AMAP, 2016) or biodiversity (CAFF, 2017), to build on existing experience and infrastructure, as further discussed below.

Similarly, a balance must be found between the use of sampling protocols developed for regions outside the Arctic and the specific conditions in the Arctic. While harmonization with global or regional protocols is desirable, they might include specifics not applicable to, or feasible for, the Arctic. For example, some shoreline litter protocols recommend three months between four seasonal monitoring campaigns. However, the number of surveys feasible to complete under Arctic conditions may be limited to one or two surveys per beach per year, which is less frequent than recommended by the Convention for the Protection of the North-East Atlantic (OSPAR) or US National Oceanic and Atmospheric Administration (NOAA) (OSPAR, 2020; Burgess et al., 2021). However, lower monitoring frequencies will affect the statistical power of spatial and temporal trend assessments. This also applies to other remote regions. Thus, experience from low-frequency sampling should be exchanged between monitoring programs, and implications for the statistical power of trend analyses should be critically assessed.

Furthermore, these guidelines are often geared toward locations with sandy or fine particulate-based shorelines, whereas Arctic and sub-Arctic shorelines are often rocky and can be ice-covered for significant periods of the year (Melvin et al., 2021). Typical minimum transect lengths (often 100 m) may in some cases not be available based on small beaches bordered by cliffs or other topographical features. This ultimately affects how litter accumulates and how these areas can be surveyed. Specific litter items may have to be added to item classification lists if they have relevance to the Arctic in terms of local uses

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

or frequent occurrences. Examples include items related to hunting and fishing activities in the Arctic or to insufficient local waste management infrastructure, as described in the AMAP Monitoring Guidelines (AMAP, 2021b). The guidelines address the challenges related to the monitoring of beach litter in the Arctic and propose a set of solutions (AMAP, 2021b).

A specific challenge of monitoring in the Arctic includes the operation of sampling equipment, especially in terms of continuous monitoring. Some monitoring systems remain in the environment for long periods of time to collect continuous data, but given the extreme winter conditions in the Arctic, this is not feasible in many regions. A lack of power supply in remote regions can also be a limiting factor. For example, a continuous and reliable power source is needed for filtration systems for high volume atmospheric/air samples. Mobile laboratory units running on solar and wind power can provide infrastructure to researchers in remote Arctic areas, but may require yearly maintenance, permissions for installing and moving units, and cause start up and maintenance costs. To overcome some of the logistic challenges, connections to existing infrastructure, including research stations, can be beneficial, as further discussed below.

The environmental conditions of the Arctic might affect plastic transport and degradation processes in ways that are different from lower latitudes. For example, freezing temperatures and exposure to sunlight can lead to embrittlement of plastics (Carroll, 1985; Cooper and Corcoran, 2010; Gewert et al., 2015), potentially generating smaller fragmented items and eventually MP particles. Sea ice is another challenge, which might act both as a barrier for larger plastic items (Cozar et al., 2017), but also as a transport vehicle of MP (Obbard, 2018; Peeken et al., 2018; Tekman et al., 2020). Diffusion rates and partitioning constants decrease with temperature, with potential consequences for a reduced leaching of chemical additives, although a higher fragmentation might counteract this effect (Tanaka et al., 2020). Thus, scientific findings from other regions may not be directly transferable to the Arctic environment and specific experimental studies are needed under Arctic conditions.

Specific knowledge from the Arctic is also needed for a more comprehensive understanding of the global sources, transport and fate of litter and MP. Thus, monitoring of litter and MP in the Arctic also holds the opportunity to link with other parts of the world, as further discussed below. Climate change progresses more rapidly in polar regions due to polar amplification, changing the Arctic environment in terms of mass balances, flows and seasonal dynamics (AMAP, 2021c; d). This change will likely affect the fate, pathways, and effects of MP (AMAP, 2021d; Welden and Lusher 2017). The most dramatic change may be the loss of permanent sea ice (AMAP, 2021c). In the wake of climate change, intensified human

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

presence and industrial activities are expected in the Arctic, likely leading to increased plastic pollution (AMAP, 2021d). It is advisable to already anticipate this change when planning future monitoring programmes in the Arctic.

Harmonization and standardization

There are currently no standardized methods for determining, assessing and reporting litter and MP in environmental samples, although work is ongoing on standardized approaches in several international frameworks, for example under the International Organization for Standardization (ISO), the United Nations (UN) and in the Regional Sea Conventions. Protocols for sampling and reporting of litter in the oceans have been established by the UN Joint Group of Experts on Scientific Aspects of Marine Environmental Pollution (GESAMP) (GESAMP, 2019). For litter on beaches and shorelines, protocols have been developed for the OSPAR region and the Marine Debris Monitoring and Assessment Project (MDMAP) of NOAA (OSPAR, 2020; Burgess et al., 2021). However, the lists of litter categories to be recorded differ between these protocols, which will affect the comparability between the OSPAR and NOAA datasets. A potential third protocol is based on the joint list for macrolitter categories adopted in the European Union (EU) under the Marine Strategy Framework Directive (MSFD) (Fleet et al., 2021). Further challenges remain in the harmonized reporting of beach litter data (Serra-Gonçalves et al., 2019). For MP, there are no harmonized or standardized measurements in monitoring approaches at present, but protocols are in preparation.

Standardization refers to the application of specific consistent methods, according to robust criteria. This has the benefit of generating comparable data needed to assess temporal and spatial trends (Provencher et al., 2017; 2019). However, defining a standardized method should not inhibit novel or iterative method development efforts. As part of method standardization processes, but especially in the field of scientific research, the issue of harmonization is of growing importance. It means that differing methods have been rigorously tested to the point that results can be viewed as comparable despite differences in methodologies. The benefit of harmonization is that data can be generated across projects that employ similar, but not necessarily identical methods. Thus, harmonization can be the first step in a standardization process.

Approaches towards harmonization and standardization of methods include global efforts to define methods, develop standard reference materials (Seghers et al., 2021) and organize interlaboratory comparisons (van Mourik et al., 2021), which is particularly important for the challenges of precise and

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

accurate MP determination. While the current efforts have confirmed that harmonization has not been achieved (van Mourik et al., 2021), the approach to strive for comparability, supported by international quality assurance/quality control (QA/QC) schemes, is important for the analytical determination of MP, including the identification of their chemical composition and quantification methods, involving different instruments and methodologies (Primpke et al., this issue). Besides, it provides the baseline for future method development including the use of new instruments for updates of monitoring guidelines and method standards. For sampling methods, standardization of components like mesh sizes for water sampling may be particularly beneficial to achieve higher comparability across studies (Michida et al., 2020).

An example of harmonization that has been achieved despite different collection methods is that of measuring and reporting plastic content in stomachs of northern fulmars *(Fulmarus glacialis)*, a common seabird in the North Atlantic and Arctic regions. Beginning in the 1980s, this bioindicator of plastic pollution has been used in the North Sea, leading to protocols and standards developed by OSPAR (OSPAR, 2008). The original protocols describe the use of beached birds (OSPAR, 2008). Due to the logistic challenges of conducting beached bird surveys in the Arctic, a different sampling strategy was adopted in the Arctic that relies on hunter collected birds and birds collected from fisheries (Trevail et al., 2015; van Franeker et al., 2021). International collaborations have ensured that analytical protocols are harmonized and result in comparable data across the northern hemisphere.

Given the substantial resources needed for each measurement in the Arctic, many Arctic samples are unique, and sample integrity, assured by rigorous QA/QC measures, is especially important. The risk of sample contamination is high, for example from the functional outdoor clothing typically worn in the Arctic, which may readily shed plastic fibres (Cai et al., 2020). As well, ship-based measurements generally bear the risk of plastic pollution artefacts, either from the vessel itself (e.g. paint flakes, grey water discharges) or plastic equipment (Dibke et al., 2021; Leistenschneider et al., 2021). Although we advocate logistic connections to initiatives undertaken for other purposes, QA/QC strategies and protocols specific to litter and MP are nonetheless essential for data quality and comparability and must be followed.

Access to open data to deduce trends

While linked to harmonized collections and standardized data reporting, data archives and access merit separate attention as these are critical for data interpretation, including the circumpolar assessment of

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.
Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

litter and MP monitoring data. This includes future analyses of spatial and temporal trends, and modelling initiatives, for example emission and transport models, as these are highly dependent on access to quality-assured and comparable monitoring data.

There is no specific database for litter and MP in the Arctic, and the best and most realistic approaches for future storage of data from various environmental Arctic media, including the terrestrial environment, remain unclear at present. If compatible with these organizations' protocols, data for beach litter could be stored in the OSPAR database for regions covered by the OSPAR area, and shoreline data from the USA could be hosted by NOAA. Data on seabed litter is currently stored in the database of the International Council for the Exploration of the Sea (ICES), which could be extended to other marine data on litter and MP. Existing databases for atmospheric data, for example EBAS hosted by the Norwegian Institute for Air Research (NILU), and/or ice and snow data housed with the National Snow and Ice Data Center (NSIDC), could possibly be extended to accommodate litter and MP data. The online portal LITTERBASE compiles data on the distribution of plastic debris and MP from scientific studies (Bergmann et al., 2017c), but it cannot facilitate the upload of extensive datasets from monitoring studies in its current form. The G20 initiative of the Organisation for Economic Co-operation and Development (OECD) has organized a global database for floating microplastics. This initiative has been coordinated by Japan (Michida et al., 2020; Isobe et al., 2021) and includes data from the Arctic. It also links with global institutions such as Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organisation (UNESCO) and may be an option for storage of MP data from long-term monitoring in surface waters.

Litter and MP data can be relatively complex, as they cover multiple environmental media (e.g. water, sediment, ice, biota for the marine environment alone), multiple parameters or combinations of these (size classes, number of items, mass, polymer type, shape, colour etc.) and associated metadata (QA/QC, location, environmental conditions, biological parameters etc.). Hence, extending existing databases is not straightforward, but requires careful consideration of the type of data presumably needed in the future. For upcoming circumpolar assessments of Arctic monitoring data, the availability of all Arctic data is crucial, preferably in one or few, compatible systems. Besides the access to all Arctic locations, the combination of data from multiple compartments in ecosystem-based approaches will be informative.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Lack of baseline and benchmark data

While for some environmental compartments and locations in the Arctic litter data exist that date back decades (e.g. litter on specific beaches in Alaska; Merrell, 1980), baseline data are lacking for most compartments. Image data from the deep Arctic seafloor have shown that plastic pollution has increased significantly over time (Parga Martínez et al., 2020), as have by-catch data from Continuous Plankton Recorder surveys from a 60-year time series (Ostle et al., 2019). However, the temporal development of environmental levels of litter and MP since the industrial production of plastics is largely unknown in the Arctic. This could be overcome through litter and MP analysis of legacy samples, such as sea ice and glacier samples, although contamination control may be unreliable. Another option is the stratigraphic analysis of sediment samples (Courtene-Jones et al., 2020; Martin et al., 2022), which could also apply to glacier cores.

However, processes of accumulation of plastics over time or local distribution are site-specific and dynamic: Mallory et al. (2021) noted that the distribution of plastic debris on low slope, sandy Arctic shorelines largely represented recent additions. However, the area lacked beach clean up activities and most of the sampled sites were well-protected from storms, so the data from many of these sites might represent all plastic that has ever washed up. These types of sites where no clean up activities take place also present an opportunity to remove the standing stock of litter and assess the rate of deposition. Monitoring and mapping the occurrence of large seafloor litter in the Arctic using imagery and trawls is complicated by the horizontal transport by currents and accumulation in depressions (Buhl-Mortensen and Buhl-Mortensen, 2017; 2018; Grøsvik et al., 2018). The relation between currents from surface to seafloor and accumulation sites for litter and plastic of all sizes will need further studies to understand the distribution patterns needed for a robust monitoring strategy.

Given that all plastic materials are man-made, a theoretical baseline of zero could be set for plastics, but might prove impractical in efforts to manage plastic pollution towards this baseline. Instead, a benchmark approach has been suggested, defining the current level of litter and/or MP in the compartments proposed for immediate monitoring (AMAP, 2021a). This level would also be the first point in a time series, and future monitoring results can be compared to this benchmark level, for example to evaluate mitigation efforts.

Furthermore, a consolidated establishment of benchmark levels of litter and MP in the Arctic across environmental compartments is challenging, as described above. Consequently, the information currently

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

available to policy-makers is incomplete, in particular with regard to temporal developments of litter and MP levels, as a basis for science-based decisions targeting the levels of litter and MP in the environment and evaluating the effectiveness of these decisions. This confirms the need to establish current levels for the prioritized indicators without further delay and with a geographical coverage that is as complete as possible for the eight Arctic countries. Nonetheless, the widespread presence of litter and MP in the Arctic has been well-established (PAME, 2019), showing that mitigation actions are needed.

Lack of knowledge of sources and transport pathways

Knowledge of sources of litter and MP in the Arctic is particularly important with a view to policy-based actions aiming at reducing litter and MP in the Arctic at their sources. Both local sources and distant sources of litter and MP have been identified in the Arctic, but their relative contributions are not known and presumably highly variable for different locations (PAME, 2019). Local sources of MP can include municipal and industrial wastewater, while litter has mostly been associated with fishing activities and solid waste (von Friesen et al., 2020; Herzke et al., 2021; PAME, 2021). The question of distant sources is closely connected with the understanding of transport pathways from lower latitudes to the Arctic as well as within the Arctic.

The presence of floating or neutrally buoyant plastic particles in the Arctic Ocean is consistent with their advection by the pathway of thermohaline circulation. Oceanographic net fluxes from the Atlantic Ocean across the Fram Strait and Barents Sea are about ten times higher than those through the Bering Strait (Eldevik and Haugan, 2020). This supports the hypothesis of a potential accumulation area in the Eurasian Arctic, as inferred from global modelling and drifter data (van Sebille et al., 2012; Cózar et al., 2017). Other processes affecting the accumulation patterns of plastics in the Arctic include riverine plumes, vertical displacements and interactions with ice and biota (van Sebille et al., 2012); however, these are not well-understood and may be further influenced by the rapidly changing climatic conditions (AMAP, 2021c).

The large Siberian rivers are main contributors of fresh water to the Arctic Ocean (Shiklomanov et al., 2021). These and other rivers can also transport plastics to the Arctic, as confirmed by a recent expedition reporting plastics of different sizes, morphology and weight in the Siberian river plumes (Yakushev et al., 2021). However, a recent study reported hardly no floating marine macrolitter items in the Kara Sea, Laptev Sea and East-Siberian Sea (Pogojeva et al., 2021). Differences in these observations could be caused by hydrography, as salty Atlantic water is placed below fresh and cold water layers from

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

rivers and the central Arctic Ocean, resulting in a patchy surface abundance of plastics (Yakushev et al., 2021). Surface plastics could also be removed from Arctic surface water to deeper layers as a consequence of downwelling. Vertical displacements of large water masses are a feature of the Arctic Ocean, forced by the formation and sinking of dense water including deep-water cascading (Wobus et al., 2013). A recent modelling study confirmed that in regions of winter convection, floating particles can be drawn down through mixing and downwelling processes, projecting increasing accumulation of MP particles over the next decades in the Central Arctic (Mountford and Maqueda, 2021).

Plastic items including MP have been recorded from deep Arctic sediments, suggesting that they are a sink of plastics (Bergmann et al., 2017b; Tekman et al., 2017), but the processes around sinking plastics are not fully understood. Furthermore, studies of large litter and plastic items on the seafloor have also indicated horizontal transport along the seabed (Buhl-Mortensen & Buhl-Mortensen, 2017). Sea ice can entrap plastics during formation and release it again upon melting, in a different place because of ice drift (Kanhai et al., 2020; Kim et al., 2021). Little is known to date regarding the variability of plastics occurrence in sea ice and how the underlying water body affects MP composition during sea ice growth (Peeken et al., 2018). A route of potentially very fast transport may be atmospheric transport, which could account for a significant contribution of MP to the ocean, especially in high latitudes (Evangeliou et al., 2020). This was corroborated by high MP levels in Arctic snow (Bergmann et al., 2019).

Models could help address these knowledge gaps and prioritize monitoring sites or sites for actions based on sources and transport processes of litter and MP. In the sub-Arctic and Arctic regions, models involve the backtracking of litter from beaches of OSPAR surveys (Strand et al., 2021), of the distribution of MP in sea ice (Peeken et al., 2018; Mountford and Maqueda, 2021) as well as high-resolution modelling of the vertical and horizontal distribution of MP in the water column (Tekman et al., 2020). Integrated modeling approaches, including freshwater inflow, could provide valuable insights into litter and MP pathways to and within the Arctic. As discussed above, processes in the Arctic may differ from those in other regions and should be considered accordingly in Arctic-specific model components.

Lack of knowledge of effects and risks of litter and microplastics

It is well-established scientifically, and prominent in the realm of public concern, that plastic debris has deleterious effects on wildlife (e.g. Vegter et al., 2014; Bucci et al., 2020). Potential impacts include entanglement of marine wildlife in plastic debris including abandoned, lost and discarded fishing gear as well as ingestion of plastic debris, while the effects of MP are studied to a lesser degree (NOAA, 2014;

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Collard and Ask, 2021). Besides direct harmful effects on an organism, the aspect of habitat destruction by litter has also been highlighted (PAME, 2019). These impacts are especially concerning in the Arctic, because wildlife species are essential subsistence, cultural, and economic resources for many local and Indigenous communities (e.g. Kinloch et al., 1992; Ford, 2009; Pannikar and Lemmond, 2020). The current knowledge base for Arctic biota, including impacts from both litter and MP, has been summarized for invertebrates (Grøsvik et al., this issue), fish (Kögel et al., this issue) as well as mammals and birds (Lusher et al., this issue), essentially documenting research initiatives, but the absence of more systematic data collections. Furthermore, macroplastic particles have been identified as a vector for transport of boreal species, in particular molluscs and algae, regarded as the main reason for re-appearance of *Mytilus* on Svalbard (Węsławski and Kotwicki, 2018).

In addition to these physical and biological impacts, there can be chemical impacts from toxic compounds that may be released from ingested plastic particles or taken up by organisms after leaching to water (Lu et al., 2019; Fauser et al., 2020). Plastic polymers contain a multitude of additives that create or ensure certain functions, such as plasticizers, flame retardants or antioxidants (Hahladakis et al., 2018; Fauser et al., 2020). The documented occurrence of plastic particles in the Arctic environment may present an additional exposure source of chemicals to wildlife and fish, besides the established long-range atmospheric and/or oceanic transport of persistent organic pollutants (POPs) to the Arctic (AMAP, 2004). While POPs are bioaccumulative by definition, some plastic additives, such as phthalates or organophosphorous flame retardants, are less likely to bioaccumulate in an organism, but might exhibit toxic effects upon uptake, through endocrine disrupting mechanisms (Net et al., 2015; Schang et al., 2016). This field of exposure to non-POP chemicals from plastic-related sources in the Arctic has not been studied in detail. Besides the complexity of a large number of polymers, associated chemicals and species involved, the processes around leaching from the polymers, environmental partitioning and bioavailability are not fully understood. The current state of knowledge is discussed by Hamilton et al. (this issue). Connected to the knowledge gaps regarding exposure, the potential effects of plastic-associated chemicals on Arctic wildlife also present an area of study where more knowledge is needed.

Impacts of litter and MP on wildlife are not only a conservation concern, but a sovereignty and food security concern for community members in the Arctic (e.g. Ford, 2009; Panikkar and Lemmond, 2020). This concern extends not only to the availability, but also to the health of wildlife for safe food consumption. Thus, the effects of litter and MP in particular extend to concerns about human health in the Arctic (PAME, 2019). Bioaccumulation of MP in animal tissue has been documented, however, current findings do not seem to suggest biomagnification processes (Miller et al., 2020; Covernton et al., 2021;

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

McIlwraith et al., 2021). Besides the accumulation in wildlife and fish, contamination of drinking water resources with MP is a worldwide concern (WHO, 2019). Current data suggest that effects of plastic particles may be most pronounced for small size classes below 10 µm, including nanoplastics (Kögel et al., 2020). Nanoplastics (< 1 µm) have recently been shown in ice from the Arctic and the Antarctic (Materić et al., 2022). However, the field of nanoplastic research is still in an early development phase. Due to limitations in the quantification of various polymer types of this size fraction, global environmental levels are largely unknown.

Opportunities

Automation

The automation of procedures is an important aspect for the evolution of environmental monitoring, in particular in remote areas. Aerial images and gliders have been used to automatically detect shoreline litter, floating marine litter and to assess effects, e.g. the entanglement of seals in litter items (Deidun et al., 2018; Claro et al., 2019; Guffogg et al., 2021). Significant advances in underwater image technology provide new opportunities to monitor seafloor litter, including effects on marine organisms. Deep learning is promising in plastic classification work, but not routinely used (Garcia-Garin et al., 2021). For MP, automated sampling remains challenging, but automation is advanced for extraction, analysis and identification (Primpke et al., 2017; da Silva et al., 2020; Lorenzo-Navarro et al., 2021). Regarding the monitoring of litter and MP in the Arctic, the future may bring some opportunities for satellite imagery, autonomous tools such as Autonomous Underwater Vehicles, wave gliders and drones.

Working on Litter and Microplastics *via* the Arctic Council

The Arctic Council celebrated its 25-year anniversary in 2021, marking two and a half decades of cooperation, coordination and interaction among the Arctic States, Arctic Indigenous peoples and other Arctic inhabitants on common Arctic issues. The topic of litter and MP is on the agenda of the Arctic Council, as expressed in the *Fairbanks Declaration* (Arctic Council, 2017) and reflected in current activities in several Arctic Council Working Groups (Figure 1). The Regional Action Plan on Marine Litter in the Arctic (PAME, 2021) will be followed by an implementation phase under the lead of PAME. The Sustainable Development Working Group (SDWG) has a focus on best practices in waste handling that can reduce sources of marine litter. CAFF focused their work on examining litter and MP in seabirds (CAFF, 2021a; 2021b), a group known to be vulnerable to plastic pollution and also prioritized for plastic

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

monitoring by AMAP (AMAP, 2021a; Provencher et al., this issue). AMAP has prepared the Monitoring Plan and Monitoring Guidelines (AMAP, 2021a; b), which are now being implemented by the Arctic States. When sufficient data are available, a circumpolar assessment is envisaged. In the meantime, the Monitoring Guidelines will be updated as new knowledge becomes available (AMAP, 2021b), and other aspects of plastic pollution in the Arctic will be addressed, amongst these the effects on ecosystems, as discussed above.

At the international symposium on “Plastics in the Arctic and Subarctic Region” hosted by the Government of Iceland in March 2021, a session was organized by the Arctic Council Working Groups on their collaborative efforts in the field of Arctic pollution (Iceland, 2021). The session reported on recent activities of the Working Groups in the field of litter and MP and analyzed potential obstacles for the next steps, such as the harsh environment of the Arctic and limited resources. Collaboration and collective actions were recognized as efficient and necessary for the way ahead, not only within the Arctic, but also with other organizations active in this field, for example the EU (Iceland, 2021).

Alignment of priorities with the concerns of northern and Indigenous communities[1]

Concern has been expressed by northern and Indigenous communities on pollution issues for decades (AMAP, 2021e), and more recently, about litter and MP (Eriksen et al., 2020). Indeed, litter and MP are now noted as priority topics in several funding programs in the Arctic, such as the Northern Contaminants Program of Canada.

Community-based monitoring can contribute to monitoring litter and MP in the Arctic region in critical and unique ways, including, but not limited to, continuity in sampling and combinations with other data and observations of relevance for environment and health. In Canada, Indigenous hunters are collaborating with research teams to contribute samples from subsistence harvests for litter and MP work, including Arctic char (*Salvelinus alpinus*) (B. Hamilton, *unpublished data*), ringed seals (*Pusa hispida)* (Bourdages et al., 2020), beluga (*Delphinapterus leucas*) (Moore et al., 2020), and walrus (*Odobenus rosmarus)* (J. Provencher, *unpublished data*). In Greenland, litter and MP monitoring involves many local contact points (J. Strand, *unpublished data*), and contaminant monitoring has been organized in collaboration with local hunters for many years (Rigét et al., 2016). The following elements have been implemented in the collaboration on litter and MP monitoring with local contacts in Greenland: i)

---

[1] This section contains text provided by Max Liboiron (Memorial University of Newfoundland and Labrador, St. John’s, NL, Canada) and Liz Pijogge (Lands and Natural Resources, Nunatsiavut Government, Nain, NL, Canada), approved by all authors.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

identifying surveyors interested in long-term involvement in community-based monitoring; ii) selection of survey sites and initiating field surveys with related training and workshops; iii) ensuring reimbursement of survey-related expenses; iv) establishing QA/QC frameworks (including e.g. photo documentation); v) facilitating data sharing (J. Strand, *unpublished data*). In northern Canada, Indigenous knowledge platforms like the Inuit Sea Ice Knowledge and Use (SIKU) programme (https://sikuatlas.ca/index.html) and other community-based programmes such as the Local Environmental Observer (LEO) network (https://www.leonetwork.org/) could be expanded to include litter observations.

The recommendations for research and monitoring expressed by an international scientific community can be different from research needs and priorities of communities and Indigenous peoples in the Arctic. Some of the methods, categories, standards, and research questions in plastic pollution research in the Arctic are skewed towards approaches common in the international scientific community (Liboiron at al., 2021, Melvin et al., 2021). Natan Obed, the President of Inuit Tapiriit Kanatami (ITK), an organization representing 65,000 Inuit in the Canadian Arctic, has written in ITK's *National Inuit Strategy for Research* that, "for far too long, researchers have enjoyed great privilege as they have passed through our communities and homeland, using public or academic funding to answer their own questions about our environment, wildlife, and people. Many of these same researchers then ignore Inuit in creating the outcomes of their work for the advancement of their careers, their research institutions, or their governments. This type of exploitative relationship must end" (p.3; ITK, 2018). ITK recommends five priority areas for research in their homelands, including: advancing Inuit governance in research, including being part of funding decisions; enhancing the ethical conduct of research, including strong community partnerships; ensuring Inuit access, ownership, and control over data and information gathered in their homelands, including monitoring data; and building capacity in Inuit research through skill-sharing, equal partnership, and research infrastructure (p. 4; ITK, 2018). While each Indigenous group and community in the Arctic will be different, many of these principles will hold across the Arctic. Pijogge and Liboiron (2021) point out that future monitoring research should align with these principles with an emphasis on the priorities of local and regional Arctic communities. These are important points to consider for methodological recommendations that come from and focus on scientific communalities. A reconciliation science approach yielded important approaches to data analysis on the abundance and types of plastic pollution in surface waters in the Eastern Arctic (Inuit Nunangat), so they aligned with Inuit governance (Liboiron et al., 2021).

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Litter and MP monitoring can also include a broader complementary citizen- and community-science component with the purpose of raising public awareness of the litter and MP problem, including its sources and impacts, and/or collecting data at a larger scale (Zettler et al., 2017; Syberg et al., 2020). To date, these citizen scientists have played a limited role in existing monitoring programs in most regions in the Arctic, but can contribute significantly to data collections, in particularly in remote areas (Bergmann et al., 2017a; Ershova et al., 2021). Most experience exists from beach litter programs, including clean-up activities (e.g. Falk-Anderson et al., 2019; Haarr et al., 2020).

An ecosystem approach, linking Arctic monitoring to the global issue of litter and microplastic pollution

The issue of litter and MP pollution in the Arctic and elsewhere often focusses on the marine environment where large amounts of litter and MP have been found all over the world (UNEP, 2014). However, the AMAP Monitoring Plan also addresses monitoring in the freshwater, terrestrial and atmospheric environment, and the AMAP Monitoring Guidelines provide technical details on monitoring approaches in these compartments (AMAP, 2021a; b; Provencher et al., this issue). They define three priority levels for monitoring: The highest priority compartments, proposed for immediate monitoring, include beaches and shorelines, seabird stomachs as well as water and sediments, while second priority approaches include the monitoring of atmospheric deposition, and the monitoring in fish and invertebrates. The water monitoring recommended as one of the monitoring approaches of highest priority is directed at both the marine and the freshwater environment, for example also targeting the rivers that discharge into the Arctic Ocean and that may be relevant sources of litter and MP to the Arctic (PAME, 2019; AMAP, 2021a).

The AMAP Monitoring Plan proposes the monitoring of atmospheric deposition as a Priority 2 activity and regards terrestrial soils as well as ice and snow as compartments for which monitoring of litter and MP needs further development. The atmospheric transport of microfibers and MP particles to the Arctic has been described (Bergmann et al., 2019) and may be a second significant transport pathway of plastics to the Arctic, besides the recognized ocean transport (Cózar et al., 2017; Evangeliou et al., 2020). Monitoring in this field, with due attention to the challenges described above, including the risk of contamination, will considerably improve the current understanding of the long-range transport of plastic particles to the Arctic. Nanoplastics will be relevant as well (Materić et al., 2021), but their determination includes many methodological challenges at present. The monitoring in ice and snow will improve our understanding of the role of the cryosphere in the transport and fate of litter and MP and thus provide possibilities to link with alpine environments and litter and MP research in the Antarctic.

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record. Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

The recommendation of monitoring terrestrial compartments reflects that sources of litter in the Arctic can be land-based, sea-based or of atmospheric origin (Bergmann et al., 2019; PAME, 2019). For example, it was recently shown that seabirds foraging at sea ingest and then deposit MP back at their terrestrial colonies (Bourdages et al., 2021), although these sites do not appear to be MP "hotspots" (Hamilton et al., 2021). However, the Monitoring Guidelines recognize that the current monitoring strategies and tools are not sufficiently developed to ensure routine monitoring in the terrestrial environment with comparable high quality data (AMAP, 2021b).

The dramatic changes that are taking place in the Arctic due to climate change have led to a remobilization and redistribution of contaminants between different environmental compartments, for example a release from melting ice to the aquatic environment (AMAP, 2021d). Similar processes are possible for litter and MP, making it particularly important to understand the interconnectivity of different compartments and the movement of microplastics between these. The multi-compartment approach that is outlined in the AMAP Monitoring Plan has the potential of ultimately connecting data from different compartments and thus moving towards an ecosystem approach that improves the holistic understanding of the transport to and distribution of litter and MP in the Arctic.

Synergies with other research and monitoring programs

A wide range of environmental monitoring and research activities are taking place throughout the Arctic. Most Arctic countries have established national contaminant monitoring programmes with a focus on organic contaminants and/or metals in biota and air that feed into the circumpolar AMAP assessments (e.g., AMAP, 2017; Rigét et al., 2019; Wong et al., 2021). CAFF has established biodiversity-based monitoring of Arctic populations (CAFF, 2017). Additional monitoring efforts taking place in the European Arctic address seafood safety with a focus on maximum limits of contaminants set by the EU and report to food safety authorities (Julshamn et al., 2013; Maage et al. 2017). Water is monitored in many locations for pH, temperature, salinity, CO_2, nitrogen, algae growth, and radioactivity (Skjerdal et al., 2017; van der Meeren and Prozorkevich, 2021). Acoustic disturbance is also monitored in some regions (Tyack et al., 2021). To minimize extra costs for litter and MP monitoring, synergies with existing programs and infrastructure may be sought. In this way, litter and MP can be efficiently implemented using harmonized or standardized procedures and repeated over time to acquire the data needed for a trend analysis.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

There are advantages and limitations to implementing new monitoring programs on existing frameworks. Given that work in the Arctic is logistically challenging and expensive (Mallory et al., 2018), there is a need to maximize the usefulness of sample collections. By collecting samples for litter and MP monitoring alongside other programs, supporting data and information (e.g. environmental and biological parameters) could be used for several purposes. The availability of additional information may also allow a broader set of questions to be addressed in relation to the fate and effects of litter and MP. Furthermore, the existing monitoring programs for contaminants in biota are designed with considerations of the statistical power needed to describe trends in the data (Rigét et al., 2019). Thus, experiences gained from contaminant monitoring regarding the natural variation in the Arctic environment can be a relevant starting point for similar evaluations in the context of litter and MP monitoring although transport and accumulation processes are likely to differ. As discussed above, studies of MP need tailored QA/QC measures that have to be integrated into existing programs if their extension to MP monitoring is intended. Sampling strategies might have to be adjusted to meet the requirements and purposes of a litter and MP monitoring programme, for example in terms of number of samples or sampling times and frequencies.

Strategies for future monitoring

Framing litter and microplastic monitoring within an Indigenous and northern research strategy

There are many ways to work with partners throughout the Arctic. The movement from ‘exclusion to self-determination in research’ as described in the *National Inuit Strategy on Research* (ITK 2018) is a useful framework for future collaboration with northern and Indigenous partners on litter and MP monitoring in the Arctic. The community-based monitoring and research on litter and MP was discussed above, including the importance of aligning several approaches to, and priorities in, research and monitoring. Examples of successful collaborations include recent work on plastic pollution in the eastern Canadian Arctic in the context of reconciliation (Liboiron et al. 2021). Given that litter and MP in the Arctic are often collected by Indigenous groups on their traditional territories, Indigenous access, ownership and control over the data should be considered during the planning of research activities.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Coordination with litter and microplastic programmes outside the Arctic

The problem of litter and MP is addressed by several organisations outside the Arctic, mainly with a focus on the marine environment and with geographical overlaps with the Arctic. These include global initiatives (e.g. GESAMP and the OECD G20 initiative), the Regional Sea Conventions such as OSPAR, the EU and national programs (e.g. NOAA). Five resolutions on marine litter have been adopted by the UN Environment Assembly (UNEA), the most recent one as of 2022 on ending plastic pollution through an international legally binding agreement (UNEA, 2022). The G20 initiative published an Action Plan on Marine Litter in 2017, and, in 2019, an implementation framework (OECD, 2017; Japan, 2020). The EU has developed a plastics strategy as part of its Circular Economy Action Plan, including actions within recycling, reduction of single-uses, developments towards circular solutions and global collaboration (EU, 2020). Regional Sea Conventions such as OSPAR and the Baltic Marine Environment Protection Commission (HELCOM) have developed Regional Action Plans for marine litter, for the Northeast Atlantic and the Baltic Sea, respectively, with items similar to the actions put forward for the Arctic (HELCOM, 2015; OSPAR, 2014; PAME, 2021). Regional efforts are also undertaken under the auspices of the Nordic Council of Ministers, also covering parts of the Arctic. The Nordic Ministerial Declaration was adopted in 2020 on the need for a global agreement to prevent marine plastic pollution (https://www.norden.org/en/declaration/nordic-ministerial-declaration-need-new-global-agreement-prevent-marine-plastic-litter). Furthermore, the Nordic cooperation developed a programme to reduce the impact of plastics (Nordic Council of Ministers, 2017).

The intergovernmental organisation ICES and its sister North Pacific Marine Science Organization (PICES) provide scientific support for monitoring in the North Atlantic and North Pacific regions. This includes work on marine litter, for example *via* the ICES Working Group for Marine Litter (WGML). The trawl surveys in the North-East Atlantic are an example of regional cooperation. Initial results are being developed within the framework of the OSPAR Quality Status Report planned in 2023. Similarly, PICES and the Northwest Pacific Action Plan (NOWPAP) are developing a strategy for monitoring litter and its impacts that does not exclude the Arctic area's environmental features.

At the regional level, the EU MSFD has mandated European states to monitor marine litter and its impacts along European coasts. These include marine areas of the European Arctic, which supports harmonisation between various programmes. The role of the Arctic is important for EU MSFD monitoring as the Arctic could provide reference levels for the definition of baselines or thresholds to determine Good Environmental Status. The NOAA MDMAP includes sites in Alaska, but these are not

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

necessarily representative of the state or region as a whole given the size and scale as well as variations from site to site. MDMAP was designed to measure and quantify shoreline debris loads, which can be repeated over time and space to make inferencesat different scales, rather than as a method to measure against a defined metric or threshold. None of the marine areas are isolated from each other and a wider geographical perspective is necessary to assess broader issues, such as the question of long-range transport of litter and MP. Bilateral collaboration, such as the Working Group on the Marine Environment of the Joint Russian-Norwegian Commission in the field of environmental protection also includes recording of litter and MP in the Barents Sea and provides possibilities for collaboration on harmonisation and standardisation of methods on monitoring programmes from the Barents Sea and the Russian Arctic. These initiatives are of major importance since they allow collaborations across national borders and common discussions on sources and measures.

The geographical overlaps and interconnections suggest that it will be useful to seek coordination and share information with regard to regional action plans, scientific advice and monitoring strategies at the regional and national level, and to feed into global initiatives coordinated by the UN. Arctic monitoring data may have special relevance as reference sites, but also for the understanding of global transport and accumulation processes. Time trend monitoring data can feed into global agreements in a similar way as established for contaminants (AMAP, 2016; 2021d). Thus, the international exchange and coordination can lead to both global indicators and regionally important metrics.

Including litter and microplastics monitoring in existing Arctic research and monitoring activities

Monitoring programmes for chemical contaminants have been in operation in the Arctic for decades. They include a suite of initiatives that collect samples (typically of air and biota, but not restricted to these matrices), determine contaminants in these samples, and contribute to the circumpolar AMAP assessments, such as those on spatial and temporal trends (AMAP, 2016; Rigét et al., 2019; Wong et al., 2021). While the monitoring of POPs and heavy metals, in particular mercury, present the backbone of these programmes, they are typically sufficiently flexible to accommodate new parameters, such as chemicals of emerging Arctic concern (AMAP, 2017). However, any extension of existing programs needs careful considerations if sampling strategies require adjustments, for example to avoid contamination.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

In the Canadian Arctic, seabirds have been collected under the Northern Contaminants Program for contaminant monitoring since the 1970s, including eggs and tissues sampled in collaboration with local Inuit community members (e.g. Braune and Letcher, 2013; Braune et al., 2014). Since 2008, seabirds collected under this program have also been used to monitor plastic ingestion and associated chemical contaminants (Poon et al., 2017; Provencher et al., 2018; Lu et al., 2019). During the dissections of seabirds in communities, it is easy to remove and sample the entire gastrointestinal tract (GIT) specifically for litter and MP analysis (Provencher et al., 2013). The removal of the intact GIT is aligned with the recommended protocols for seabird monitoring and thus provides standardized metrics for global comparisons (Provencher et al., 2017; 2019).

The contaminant monitoring under AMAP also includes a human health programme focusing on exposure to and effects of POPs and heavy metals on the human population of the Arctic (AMAP, 2021e). Similar to the contaminant monitoring in biota, ongoing activities could be extended to include studies on litter and MP, in close collaboration with local communities.

In addition to the contaminant-focused monitoring programs, there are a variety of other programmes suitable for collecting samples and providing information on litter and MP in the Arctic. In the Canadian Arctic, fisheries monitoring programs have collected samples of Arctic char (*Salvelinus alpinus*) for litter and MP assessments (B. Hamilton, *unpublished data*). Additionally, some research programs can collect non-target species, such as bycatch in fisheries, for litter and MP monitoring. This has been applied in Arctic Canada where fulmars accidentally caught by fisheries (Anderson et al., 2018) have been examined for plastics (Mallory et al., 2006). In the Barents Sea, the Norwegian-Russian ecosystem cruises, which contribute to the population monitoring of fish species for sustainable catch, now house manta trawling equipment for plastic in water and plankton, and they also record floating litter and litter as bycatch in trawls (Grøsvik et al., 2018; van der Meeren & Prozorkevich 2021). While this opportunistic, yet targeted sampling presents an optimized use of resources and could enable access to locations that could not be visited otherwise, the specific QA/QC requirements for sampling of litter and MP need to be rigorously integrated in sampling campaigns with a different primary focus, in particular for the MP component. This also includes sample storage, transport and pre-processing, prior to the actual MP analysis.

Ships of opportunity can also be used to survey litter on the water surface or to collect MP with designated samplers, as further discussed below. Mallory et al. (2021) reported floating litter throughout the Canadian Arctic as part of bird surveys aboard expedition cruise vessels. Based on at-sea surveys covering 263,543 km of marine survey transects, anthropogenic debris was observed floating in marine

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.
Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

waters from the southeastern coast of North America into the Canadian Arctic, north to ~78° N. Over this region, 1,266 pieces of floating debris were observed, of which 74% were plastics (Mallory et al., 2021). Interestingly, these results differed somewhat from Bergmann et al. (2016), who, on a different vessel, found that all floating debris in the Fram Strait and Barents Sea was plastic. Such data collection approaches may help fill in knowledge gaps in regions where only a few vessels transit each year, and consequently, expensive, systematic surveys may simply be impractical.

Use of established networks of Arctic Research Stations

Permanent or long-term infrastructure in the Arctic provides possibilities for new monitoring platforms for litter and MP, in particular *via* existing networks of Arctic research and monitoring stations. Several Arctic monitoring stations focussing on the terrestrial environment are linked in the INTERACT network (International Network for Terrestrial Research and Monitoring in the Arctic; https://eu-interact.org/). This focus on the terrestrial environment could provide a relevant complementary component to marine monitoring activities, and thus support the ecosystem approach envisaged for litter and MP in the Arctic environment. In Canada, a large number of stations, facilities and structures are organized in the Canadian Network for Northern Research Operators (http://cnnro.ca/our-facilities/), also providing contact points in different locations and environments.

The HAUSGARTEN observatory in the eastern Fram Strait was originally installed to observe the impact of climate change from the sea surface to the deep seafloor at 21 sampling stations located along a bathymetric (250 -5500 m depth) and latitudinal gradient (Soltwedel et al., 2016). It has recently also been used to assess litter and MP in different ecosystem compartments following an observation of increasing litter quantities in deep-sea photographs (Bergmann et al, 2016; Tekman et al., 2017; 2020; Parga Martinez et al., 2020). Its platforms such as benthic landers and year-round moorings with sediment traps along with annual sampling campaign using an ice breaker targeting all ecosystem compartments facilitate regular access that is needed for trend analyses. Legacy photographs from seafloor surveys could be used to assess seafloor litter pollution and increase our knowledge of its distribution throughout the Arctic.

The opportunities related to the collaborative use of existing research infrastructure for studies of plastics in the marine environment were recently presented by Ó Conchubhair et al. (2019). The authors highlighted the European Strategy Forum on Research Infrastructure (ESFRI), which could play a role in European initiatives addressing plastic debris in the marine environment. Microplastics could be sampled

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

in the Arctic with FerryBox systems on ships of opportunities (Ó Conchubhair et al., 2019). This was recently tested for microplastic samplers on ferries crossing Danish waters and could be extended to the Arctic, including tailored QA/QC protocols (Lusher et al., 2021).

Monitoring sources and accountability measures

With marine plastic pollution research becoming more common in scientific communities and crowdsourced initiatives globally, there are calls within non-governmental organizations, and advocate communities that are impacted by marine plastic pollution for another type of approach to methods and metrics, accounting for sources of plastic pollution. This includes both methods (what is observed, where it is observed, and to what ends) and metrics (what is counted, what categories are salient). Accountability measures are uniquely suited to inform action on mitigating or eliminating sources of marine plastic pollution.

The most developed accountability measure in marine plastic pollution is the brand audit, popularized by the global #breakfreefromplastic movement (BFFP, 2021). A brand audit records plastic items where brand names of items are apparent. It has been carried out worldwide on an annual basis (BFFP, 2021) Recording counts of items by brand is designed to show the industrial origin (often called a "parent company") of marine plastics, and is tied with extended producer responsibility (EPR), where producers of waste are responsible for the fate of their packaging products. The use of such accountability measures in the Arctic would allow mitigation measures to be directed to those types of pollution that are the most prevalent ones, while offering linkages to other parts of the world. Despite regional differences, products of companies with worldwide markets have also been found all over the word (BFFP, 2019).

Another form of accountability measures may be introduced in relation to fishing gear, a major pollutant in many regions of the Arctic (Buhl-Mortensen and Buhl-Mortensen, 2017; PAME, 2019). Annual clean-up surveys in the most important fishing grounds along the Norwegian coast have removed over 1000 tonnes of gear since 1983, including 22,000 gill nets with a combined length of over 600 km (https://www.fiskeridir.no/English/Fisheries/Marine-litter/Retrieval-of-lost-fishing-gear). The Food and Agricultural Organization (FAO) of the UN has developed voluntary guidelines for marking fishing gear (FAO, 2019), which PAME (2021) supports as an action for the Arctic. Likewise, a required reporting of lost fishing gear, as part of national regulations, has been suggested as an action for the Arctic (PAME, 2021). In total, of the 59 actions in the Regional Action Plan on Marine Litter in the Arctic, eleven relate to fisheries and others target ship traffic, waste handling and similar waste sources (PAME, 2021).

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Conclusions

The monitoring of litter and MP in the Arctic has been initiated under the auspices of AMAP, with the purpose of generating information for regulatory bodies, addressing research priorities of northern and Indigenous communities and contributing to a better scientific understanding of a global pollution issue. Current challenges are related to the specific environmental conditions of the Arctic, the lack of standardization and harmonization, in both measurements and reporting, as well as major knowledge gaps with regard to baselines and benchmarks, sources, transport and effects of litter and MP. These challenges need consideration for the newly established monitoring programme to be successful, including careful definitions of monitoring purposes and related strategies, both in terms of scientific approaches and feasibility. The well-established networks under AMAP and other Arctic Council Working Groups, for example from long-term monitoring of contaminants or biodiversity, can facilitate the exchange of knowledge and experience between the Arctic States. In addition, the infrastructure used in other Arctic monitoring programmes and research projects could provide a platform for the litter and MP monitoring to build on. Thus, synergies are possible and should be explored, however, always keeping in mind that litter and MP monitoring needs rigorous QA/QC measurements to ensure accurate and precise data. Engaging with Arctic communities in the development and implementation of this research and monitoring will not only help address inequities of past approaches and help adhere to recommended ethical practices, but should also provide new options for data collection that were not considered in the past. Additionally, benefits accrue in learning from past experiences and exploring multi-purpose uses of supporting data. Aspects of human health might be included in future developments of monitoring strategies, being directly linked with pollution issues in the Arctic environment, accumulation of MP and other contaminants in wildlife and resulting concerns about food security.

The monitoring of litter and MP in the Arctic has to find a balance between Arctic-related specific questions and the link to the global pollution issue of litter and MP. The current programme offers possibilities of an ecosystem approach, improving the understanding of linkages between environmental compartments within the Arctic, also taking into account the rapid dynamics in the Arctic environment caused by climate change, as well as the geographically broader view on transport pathways and source regions. Ultimately, data from the Arctic will be an important element in broad-scale international approaches to the problem of litter and MP pollution, through reference data, elucidation of transport pathways and sources, and trend data for evaluations of mitigation actions.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Acknowledgements

The authors wish to thank Max Liboiron and Liz Pijogge for critical discussions, insights into community-based research in Arctic Canada and information about the Inuit Tapiriit Kanatami and its *National Inuit Strategy on Research*, including text provided for the section on “Alignment of priorities with the concerns of northern and Indigenous communities”.

KV and JS acknowledge funding from the programme *Miljøstøtte til Arktis* of the Danish Environmental Protection Agency. MG acknowledges financial support from the Swedish Environmental Protection Agency. BEG and TK were funded through the Institute of Marine Research, Bergen, Norway by the Ministry of Trade, Industry and Fisheries, Norway. BMH acknowledges funding support from the Northern Contaminants Program of Canada and the University of Toronto. This publication is Eprint ID 54463 of the Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar und Meeresforschung and benefits from the Pollution Observatory of the Helmholtz-funded programme FRAM (Frontiers in Arctic Marine Research). MBe and IP are funded by the PoF IV program “Changing Earth - Sustaining our Future” Topic 6.4 of the German Helmholtz Association. FG, ALL, SP and JS acknowledge that this work contributes to part of a project that has received funding from European Union’s Horizon 2020 Coordination and Support Action programme under Grant Agreement 101003805 (EUROqCHARM).

Competing interests

The authors have no competing interests.

Author contributions

JP: Conceptualization, methodology, writing – original draft, writing – review & editing, visualization, project administration; SA: Conceptualization, writing – original draft, writing – review & editing; MBe: Conceptualization, writing – review & editing; MBo: Conceptualization, writing – review & editing; LB-M: Conceptualization, writing – review & editing; FG: Conceptualization, writing – original draft, writing – review & editing; AG: Conceptualization, writing – review & editing; MG: Conceptualization, writing – review & editing; BEG: Conceptualization, writing – review & editing; BMH: Conceptualization, writing – review & editing, visualization; TK: Conceptualization, writing – review & editing; JRL: Conceptualization, methodology, writing – review & editing, project administration, ALL: Conceptualization, writing – review & editing; MLM: Conceptualization, writing – review & editing; PM: Conceptualization, writing – review & editing; IP: Conceptualization, writing – review & editing;

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record. Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

SP: Conceptualization, writing – review & editing; JS: Conceptualization, writing – review & editing; KV: Conceptualization, methodology, validation, writing – original draft, writing – review & editing, funding acquisition

References

AMAP (2004) AMAP Assessment 2002: Persistent Organic Pollutants in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xvi + 310 pp.

AMAP (2016) AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, vi + 71 pp.

AMAP (2017) AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xvi + 353 pp.

AMAP (2021a) AMAP Litter and Microplastics Monitoring Plan. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, 23 pp.

AMAP (2021b) AMAP Litter and Microplastics Monitoring Guidelines. Version 1.0. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, 257 pp.

AMAP (2021c) Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy Makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

AMAP (2021d). POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change. Summary for Policy Makers, Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

AMAP (2021e) Human Health in the Arctic. Summary for Policy Makers, Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

Anderson, C.M.; Iverson, S.A.; Black, A.; Mallory, M.L.; Hedd, A.; Merkel, F.; Provencher, J.F. (2018) Modelling demographic impacts of a growing Arctic fishery on a seabird population in Canada and Greenland. Mar. Environ. Res. 142, 80-90.

Arctic Council (2017) Fairbanks Declaration, 16 pp.

Baak, J.E.; Provencher, J.F.; Mallory, M.L. (2020) Plastic ingestion by four seabird species in the Canadian Arctic: Comparisons across species and time. Mar. Pollut. Bull. 158, 111386.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

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

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

Bergmann, M.; Wirzberger, V.; Krumpen, T.; Lorenz, C.; Primpke, S.; Tekman, M.B.; Gerdts, G. (2017b) High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN Observatory. Environ. Sci. Technol. 51, 11000-11010.

Bergmann, M.; Tekman, M.; Gutow, L. (2017c) Sea change for plastic pollution. Nature 544, 297.

Bergmann, M.; Mützel, S.; Primpke, S., Tekman, M.B.; Trachsel, J.; Gerdts, G. (2019) White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. 5 (8), eaax1157.

BFFP (2019) BRANDED, Vol. II. Identifying the world's top corporate plastic polluters. https://www.breakfreefromplastic.org/globalbrandauditreport2019/

BFFP (2021) BRANDED, Vol. IV. Holding corporations accountable for the plastic & climate crisis. https://www.breakfreefromplastic.org/brandaudit2021/

Bourdages, M.P.T.; Provencher, J.F.; Sudlovenick, E.; Ferguson, S.H.; Young, B.G.; Pelletier, N.; Murphy, M.J.J.; D'Addario, A.; Vermaire, J.C. (2020) No plastics detected in seal (Phocidae) stomachs harvested in the eastern Canadian Arctic. Mar. Pollut. Bull. 150, 110772.

Bourdages, M.P.T.; Provencher, J.F.; Baak, J.E.; Mallory, M.L.; Vermaire, J.C. (2021) Breeding seabirds as vectors of microplastics from sea to land: Evidence from colonies in Arctic Canada. Sci. Total Environ. 764, 142808.

Braune, B.; Letcher, R.J. (2013) Perfluorinated sulfonate and carboxylate compounds in eggs of seabirds breeding in the Canadian Arctic: Temporal trends (1975-2011) and interspecies comparison. Environ. Sci. Technol. 47, 616-624.

Braune, B.M.; Gaston, A.J.; Gilchrist, H.G.; Mallory, M.L.; Provencher, J.F. (2014) A geographical comparison of mercury in seabirds in the eastern Canadian Arctic. Environ. Int. 66, 92-96.

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

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

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Buhl-Mortensen, P.; Buhl-Mortensen, L. (2018) Impacts of bottom trawling and litter on the seabed in Norwegian waters. Front. Mar. Sci. 5:42.

Burgess, H.K.; Herring, C.E.; Lippiatt, S.; Lowe, S.; Uhrin, A.V. (2021) NOAA Marine Debris Monitoring and Assessment Project Shoreline Survey Guide. National Oceanic and Atmospheric Administration Marine Debris Program.

CAFF (2017) State of the Arctic Marine Biodiversity Report. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland. ISBN 978-9935-431-63-9.

CAFF (2021a) Plastic pollution in seabirds. Developing a program to monitor plastic pollution in seabirds in the pan-Arctic region. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland. ISBN 978-9935-431-87-5.

CAFF (2021b) Plastic ingestion by seabirds in the circumpolar Arctic: A review. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland. ISBN 978-9935-431-88-2.

Cai, Y.; Yang, T.; Mitrano, D.M.; Heuberger, M.; Hufenus, R.; Nowack, B. (2020) Systematic study of microplastic fiber release from 12 different polyester textiles during washing. Environ. Sci. Technol. 54, 4847-4855.

Carroll, M.M. (1985) Polyvinylchloride (PVC) pipe reliability and failure modes. Reliability Engineering 13, 11-21.

Carpenter, E.J.; Anderson, S.J.; Harvey, G.R.; Miklas, H.P.; Peck, B.B. (1972) Polystyrene spherules in coastal waters. Science 178, 749-750.

Claro, F.; Fossi, M.; Ioakeimidis, C.; Baini, M.; Lusher, A.; Mc Fee, W.; McIntosh, R.; Pelmatti, T.; Sorce, M.; Galgani, F.; Hardesky, B.D. (2019) Tools and constraints in monitoring interactions between marine litter and megafauna: Insights from case studies around the world. Mar. Pollut. Bull. 141, 147-160.

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

Cooper, D.A.; Corcoran, P.L. (2010) Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. Mar. Pollut. Bull. 60, 650-654.

Courtene-Jones, W.; Quinn, B.; Ewins, C.; Gary, S.F.; Narayanaswamy, B.E. (2020) Microplastic accumulation in deep-sea sediments from the Rockall Trough. Marine Pollut. Bull. 154, 111092.

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.
Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

Covernton, G.A.; Davies, H.L.; Cox, K.D.; El-Sabaawi, R.; Juanes, F.; Dudas, S.E.; Dower, J.F. (2021) A Bayesian analysis of the factors determining microplastics ingestion in fishes. J. Hazard. Mater. 413: 125405.

Cózar, A.; Echevarría, F.; González-Gordillo, J.I.; Irigoien, X.; Úbeda, B.; Hernández-León, S.; Palma, Á.T.; Navarro, S.; García-de-Lomas, J.; Ruiz, A.; Fernández-de-Puelles, M.L.; Duarte, C.M. (2014) Plastic debris in the open ocean. Proceedings of the National Academy of Sciences 111, 10239-10244.

Cózar, A.; Martí, E.; Duarte, C.M.; García-de-Lomas, J.; van Sebille, E.; Ballatore, T.J.; Eguílez, V.M.; González-Gordillo, J.I.; Pedrotti, M.L.; Echevarría, F.; Troublè, R.; Irigoien, X. (2017) The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation. Sci. Adv. 3:e1600582.

da Silva, V.H.; Murphy, F.; Amigo, J.M.; Stedmon, C.; Strand, J. (2020) Classification and quantification of microplastics (< 100 μm) using a Focal Plane Array-Fourier Transform Infrared imaging system and machine learning. Anal. Chem. 92, 13724-13733.

Deidun, A.; Gauci, A.; Lagorio, S.; Galgani, F. (2018) Optimising beached litter monitoring protocols through aerial imagery. Mar. Pollut. Bull. 131, 212-217.

Dibke, C.; Fischer, M.; Scholz-Böttcher, B.M. (2021) Microplastic mass concentrations and distribution in German Bight waters by pyrolysis-gas chromatography-mass spectrometry/thermochemolysis reveal potential impact of marine coatings: Do ships leave skid marks? Environ. Sci. Technol. 55, 2285-2295.

Eriksen, M.; Borgogno, F.; Vallarrubia-Gómez, P.; Anderson, E.; Box, C.; Trenholm, N. (2020) Mitigation strategies to reverse the rising trend of plastics in Polar Regions. Environ. Int. 139, 105704.

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

EU (2020) A new Circular Economy Action Plan – For a cleaner and more competetive Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, 11.3.2020, COM(2020) 98 final.

Evangelious, N.; Grythe, H.; Klimont, Z.; Heyes, C.; Eckhardt, S.; Lopez-Aparicio, S.; Stohl, A. (2020) Atmospheric transport is a major pathway of microplastics to remote regions. Nat. Commun. 11:3381.

Falk-Andersson, J.; Berkhout, B.W.; Abate, T.G. (2019) Citizen science for better management: Lesssons learned from three Norwegian beach litter data sets. Mar. Pollut. Bull. 138, 364-375.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

FAO (2019) Voluntary Guidelines on the Marking of Fishing Gear. Food and Agricultural Organisation of the United Nations, Rome, Italy, 88 pp. Licence CC BY-NC-SA 3.0 IGO.

Fauser, P.; Strand, J.; Vorkamp, K. (2020) Risk assessment of added chemicals in plastics in the Danish marine environment. Mar. Pollut. Bull. 157, 111298.

Fleet, D.; Vlachogianni, T.; Hanke, G. (2021) A joint list of litter categories for marine macrolitter monitoring. EUR 30348 EN, Publications Office of the European Union, Luxembourg 2021. ISBN 978-92-76-21445-8 (online).

Ford, J.D. (2009) Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case study from Igloolik, Nunavut. Reg. Environ. Change 9, 83-100.

Garcia-Garin, O.; Monleón-Getino, T.; López-Brosa, P.; Borrell, A.; Aguilar, A.; Borja-Robalino, R.; Cardona L.; Vighi, M.(2021) Automatic detection and quantification of floating marine macro-litter in aerial images: Introducing a novel deep learning approach connected to a web application in R. Environ. Pollut. 273, 116490.

GESAMP (2016) Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. (P.J. Kershaw and C.M. Rochman, eds). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 93.

GESAMP (2019) Guidelines for the monitoring and assessment of plastic litter in the ocean (P.J. Kershaw, A. Turra and F. Galgani, eds). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/ UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP No. 99.

Gewert, B.; Plassmann, M.M.; MacLeod, M. (2015) Pathways for degradation of plastic polymers floating in the marine environment. Environ Sci.: Processes Impacts 17, 1513-1521.

Granberg, M.; von Friesen, L.W.; Ask, A.; Collard, F.; Magnusson, K.; Wiklund, A.-K.E.; Murphy, F.; Strand, J.; Gabrielsen, G.W.; Bach, L. (2020) Microlitter in arctic marine benthic food chains and potential effects on sediment dwelling fauna. TemaNord 2002: 528, Nordic Council of Ministers, Copenhagen, Denmark; ISBN 978-92-893-6686-1.

Grøsvik, B.E.; Prokhorova, T.; Eriksen, E.; Krivosheya, P.; Horneland, P.A.; Prozorkevich, D. (2018) Assessment of marine litter in the Barents Sea, a part of the joint Norwegian-Russian ecosystem survey. Front. Mar. Sci. 5:72.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Grøsvik, B.E.; Granberg, M.; Kögel, T.; Lusher, A.; Gomiero, A.; Halldorsson, H.P.; Madsen, A.K.; Baak, J.E.; Guls, H.D.; Magnusson, K. (2022) Microplastics in Arctic invertebrates – status on occurrence and recommendations for future monitoring. Arctic Sci. (this issue)

Guffogg, J.; Soto-Berelov, M.; Jones, S.D.; Bellman, C.J.; Lavers, J.L.; Skidmore, A.K. (2021) Towards the spectral mapping of plastic debris on beaches. Remote Sens. 13, 1850.

Haarr, M.L.; Pantalos, M.; Hartviksen, M.K.; Gressetvold, M. (2020) Citizen science data indicate a reduction in beach litter in the Lofoten archipelago in the Norwegian Sea. Mar. Pollut. Bull. 153, 111000.

Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. (2018) An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mat. 344, 179-199.

Halsband, C.; Herzke, D. (2019) Plastic litter in the European Arctic: What do we know? Emerg. Contam. 5, 308-318.

Hamilton, B.M.; Bourdages, M.P.T.; Geoffroy, C.; Vermaire, J.C.; Mallory, M.L.; Rochman, C.M.; Provencher, J.F. (2021) Microplastics around an Arctic seabird colony: Particle community composition varies across environmental matrices. Sci. Total Environ. 773, 145536.

Hamilton, B.M.; Baak, J.E.; Vorkamp, K.; Hammer, S.; Granberg, M.; Herzke, D.; Provencher, J.F. (subm.) Plastics as a carrier of chemical additives to the Arctic: Possibilities for strategic monitoring across the circumpolar North. Arctic Sci. (this issue)

HELCOM (2015) Regional Action Plan for Marine Litter in the Baltic Sea, 20 pp.

Herzke, D.; Ghaffari, P.; Sundet, J.H.; Tranang, C.A.; Halsband, C. (2021) Microplastic fiber emissions from wastewater effluents: Abundance, transport behavior and exposure risks for biota in an Arctic fjord. Front. Environ. Sci. 9. 662168.

Iceland (2021) International Symposium on Plastics in the Arctic and the Sub-Arctic Region, Symposium Summary. The Government of Iceland and the Nordic Council of Ministers.

Isobe, A.; Azuma, T.; Cordova, C.; Cózar, A.; Galgani, F.; Hagita, R.; Kanhai, L.; Imai, K.; Iwasaki, S.; Kako, S.; Kozlovskii, N.; Lusher, A.; Mason, S.A.; Michida, Y.; Mituhasi, T.; Morii, Y.; Mukai, T.; Popova, A.; Shimizu, K.; Tokai, T.; Uchida, K.; Yagi, M.; Zhang, W. (2021) A multilevel dataset of microplastic abundance in the world's upper ocean and the Laurentian Great Lakes . Microplastics and Nanoplastics 1:16.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

ITK 2018. National Inuit Strategy on Research. Inuit Tapiriit Kanatami. https://www.itk.ca/national-strategy-on-research-launched/

Japan (2020) G20 report on actions against marine plastic litter. Second information sharing based on the G20 Implementation Framework. Ministry of the Environment, Japan, 2nd edition (as of 30 November 2020).

Julshamn, K.; Duinker, A.; Nilsen, B.M.; Frantzen, S.; Maage, A.; Valdersnes, S.; Nedreaas, K. (2013) A baseline study of levels of mercury, arsenic, cadmium and lead in Northeast Arctic Cod *(Gadus morhua)* from different parts of the Barents Sea. Mar. Pollut. Bull. 67, 187-195.

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

Kim, S.-K.; Lee, H.-J.; Kim, J.-S.; Kang, S.-H.; Yang, E.-J.; Cho, K.-H.; Tian, Z.; Andrady, D. (2021) Importance of seasonal sea ice in the western Arctic ocean to the Arctic and global microplastic budgets. J. Hazard. Mat. 418, 125971.

Kinloch, D.; Kuhnlein, H.; Muir, D.C.G. (1992) Inuit foods and diet: a preliminary assessment of benefits and risks. Sci. Total Environ. 122, 247-278.

Kögel, T.; Bjorøy, Ø.; Toto, B.; Bienfait, A.M.; Sanden, M. (2020) Micro- and nanoplastic toxicity on aquatic life: Determining factors. Sci. Total Environ. 709, 136050.

Kögel, T.; Hamilton, B.M.; Granberg, M.E.; Provencher, J.; Hammer, S.; Gomiero, A.; Magnusson, K.; Lusher, A.L. (subm.) Current efforts on microplastic monitoring in Arctic fish and how to proceed. Arctic Sci. (this issue)

Leistenschneider, C.; Burkhardt-Holm, P.; Mani, T.; Primpke, S.; Taubner, H.; Gerdts, G. (2021) Microplastics in the Weddell Sea (Antarctica): A forensic approach for discrimination between environmental and vessel-induced microplastics. Environ. Sci. Technol. 55, 15900-15911.

Lorenzo-Navarro, J.; Castrillón-Santana, M.; Sánchez-Nielsen, E.; Zarco, B.; Herrera, A.; Martínez, I.; Gómez, M. (2021) Deep learning approach for automatic microplastics counting and classification. Sci.Total Environ. 765, 142728.

Liboiron, M.; Zahara, A.; Hawkins, K.; Crespo, C.; de Moura Neves, B.; Wareham-Hayes, V.; Edinger, E.; Muise, C.; Walzak, M.J.; Sarazen, R.; Chidley, J.; Mills, C.; Watwood, L.; Arif, H.; Earles, E.; Pijogge, L.; Shirley, J.; Jacobs, J.; McCarney, P.; Charron, L. (2021) Abundance and types of plastic

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

pollution in surface waters in the Eastern Arctic (Inuit Nunangat) and the case for reconciliation science. Sci. Total Environ. 782, 146809.

Lu, Z.; De Silva, A.O.; Provencher, J.F.; Mallory, M.L.; Kirk, J.L; Houde, M.; Stewart, C.; Braune, B.M.; Avery-Gomm, S.; Muir , D.C.G. (2019) Occurrence of substituted diphenylamine antioxidants and benzotriazole UV stabilizers in Arctic seabirds and seals. Sci. Total Environ. 663, 950-957.

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

Lusher, A.; Singdahl-Larsen, C.; Jaccard, P.F.; van Bavel, B.; Valestrand, L.; Harvey, E.T.; Andersen, J.H. (2021) Frequent sampling of microplastic particles in surface waters in the open parts of the Kattegat and Great Belt, Denmark. Norwegian Institute for Water Research (NIVA), report no. 7601-2021. https://niva.brage.unit.no/niva-xmlui/handle/11250/2735983

Lusher, A.L.; Provencher, J.F.; Baak, J.E.; Hamilton, B.M.; Vorkamp, K.; Hallanger, I.G.; Pijogge, L.; Liboiron, M.; Bourdages, M.P.T.; Hammer, S.; Gavrilo, M.; Vermaire, J.C.; Linnebjerg, F.J.; Mallory, M.L.; Gabrielsen, G.W. (2022) Monitoring litter and microplastics i Arctic mammals and birds. Arctic Sci. (this issue)

Maage, A.; Nilsen, B.M.; Julshamn, K.; Frøyland, L.; Valdersnes, S. (2017) Total mercury, methylmercury, inorganic arsenic and other elements in meat from minke whale *(Balaenoptera acutorostrata)* from the North East Atlantic Ocean. Bull. Environ. Contam. Toxicol. 99, 161-166.

Mallory, M.; Robertson, G.J.; Moenting, A. (2006) Marine plastic debris in northern fulmars from Davis Strait, Nunavut, Canada. Mar. Pollut. Bull. 52, 813-815.

Mallory, M.L.; Gilchrist, H.G.; Janssen, M.; Major, H.L.; Merkel, F.; Provencher, J.F.; Strøm, H. (2018) Financial costs of conducting science in the Arctic: examples from seabird research. Arct. Sci. 4, 624-633.

Mallory, M.L.; Baak, J.; Gjerdrum, C.; Mallory, O.E.; Manley, B.; Svan, C.; Provencher, J.F. (2021) Anthropogenic litter in marine waters and coastlines of Arctic Canada and West Greenland. Sci. Total Environ. 783, 146971.

Martin, J.; Lusher, A.L.; Nixon, F.C. (2022) A review of the use of microplastics in reconstructing dated sedimentary archives. Sci. Total Environ. 806, 150818.

Materić, D.; Kjær, H.A.; Vallelonga, P.; Tison, J.-L.; Röckmann, T.; Holzinger, R. (2022) Nanoplastics measurements in Northern and Southern polar ice. Environ. Res. 208, 112741.

© The Author(s) or their Institution(s)

For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.
Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22

McIlwraith, H.K.; Kim, J.; Helm, P.; Bhavsar, S.P.; Metzger, J.S.; Rochman, C.M. (2021) Evidence of microplastic translocation in wild-caught fish and implications for microplastic accumulation dynamics in food webs. Environ. Sci. Technol. 55, 12372-12382.

Melvin, J.; Bury, M.; Ammendolia, J.; Mather, C.; Liboiron, M. (2021) Critical gaps in shoreline plastics pollution research. Front. Mar. Sci. 8, 689108.

Merrell, T.R. Jr. (1980) Accumulation of plastic litter on beaches of Amchitka Island, Alaska. Mar. Environ. Res. 3, 171-184.

Michida, Y.; Chavanich, S.; Cózar, A.; Galgani, F.; Hagmann, P.; Hinata, H.; Isobe, A.; Kershaw, P.; Kozlovskii, N.; Li, D.; Lusher, A.; Marti, E.; Mason, S.; Mu, J.; Saito, H.; Shim, W.; Syakti, A.D.; Takada, H.; Thompson, R.; Tokai, T.; Uchida, K.; Vasilenko, K.; Wang, J. (2020) Guidelines for harmonizing ocean surface microplastic monitoring methods. Ministry of the Environment, Japan, 71 p, https://www.env.go.jp/en/water/marine_litter/guidelines/guidelines.pdf

Miller, M.E.; Hamann, M.; Kroon, F.J. (2020) Bioaccumulation and biomagnification of microplastics in marine organisms: A review and meta-analysis of current data. PLoS ONE 15(10): e0240792.

Mishra, A.K.; Singh, J.; Mishra, P.P. (2021) Microplastics in polar regions: An early warning to the world’s pristine ecosystem. Sci. Total Environ. 784, 147149.

Moore, R.C.; Loseto, L.; Noel, M.; Etemadifar, A.; Brewster, J.D.; MacPhee, S.; Bendell, L.; Ross, P.S. (2020) Microplatsics in beluga whales *(Delphinapterus leucas)* from the Eastern Beaufort Sea. Mar. Pollut. Bull. 150, 110723.

Mountford, A.S.; Maqueda, M.A.M. (2021) Modeling the accumulation and transport of microplastics by sea ice. J. Geophys. Res. Oceans 126:e2020JC016826.

Net, S.; Sempéré, R.; Delmont, A.; Paluselli, A.; Ouddane, B. (2015) Occurrence, fate, behavior and ecotoxicological state of phthalates in different environmental matrices. Environ. Sci. Technol. 49, 4019-4035.

NOAA (2014) Report on the entanglement of marine species in marine debris with an emphasis on species in the United States. National Oceanic and Atmospheric Administration Marine Debris Program. Silver Spring, MD, USA, 28 pp.

Nordic Council of Ministers (2017) Nordic Programme to Reduce the Environmental Impact of Plastic. ISBN (print) 978-92-893-5000-6

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Ó Conchubhair, D.; Fitzhenry, D.; Lusher, A.; King, A.I.; van Emmerik, T.; Lebreton, L.; Ricaurte-Villota, C.; Espinosa, L.; O'Rourke, E. (2019) Joint effort among research infrastructures to quantify the impact of plastic debris in the ocean. Environ. Res. Lett. 14, 065001.

Obbard, R.W. (2018) Microplastics in polar regions: The role of long range transport. Curr. Opin. Environ. Sci. Health 1, 24-29.

Obbard, R.W.; Sadri, S.; Wong, Y.Q.; Khitun, A.A.; Baker, I.; Thompson, R.C. (2014) Global warming releases microplastic legacy frozen in Arctic sea ice. Earth's Future 2, 315-320.

OECD (2017) G20 Action Plan on Marine Litter, G20 Germany 2017, HamburgOSPAR (2008) Background document for the EcoQO on plastic particles in stomachs of seabirds. OSPAR, London, UK.

OSPAR (2020) CEMP Guidelines for marine monitoring and assessment of beach litter (OSPAR Agreement 2020-02). https://www.ospar.org/documents?v=44122

OSPAR (2014) Regional Action Plan for Prevention and Management of Marine Litter in the North-East Atlantic. OSPAR, London, UK. ISBN 978-1-906840-86-0

Ostle, C.; Thompson, R.C.; Broughton, D.; Gregory, L.; Wootton, M.; Johns, D.G. (2019) The rise in ocean plastics evidenced from a 60-year time series. Nat. Commun. 10:1622.

PAME (2019) Desktop Study on Marine Litter including Micoplastics in the Arctic. Protection of the Arctic Marine Environment (PAME), May 2019.

PAME (2021) Regional Action Plan on Marine Litter in the Arctic. Protection of the Arctic Marine Environment (PAME), May 2019.

Panikkar, B.; Lemmond, B. (2020) Being on land and sea in troubled times: Climate change and food sovereignty in Nunavut. Land 9, 508.

Parga Martinez, K.B.; Tekman, M.B.; Bergmann, M. (2020) Temporal trends in marine litter at three stations of the HAUSGARTEN Observatory in the Arctic deep sea. Front. Mar. Sci. 7:321

Peeken, I.; Primpke, S.; Beyer, B.; Gütermann, J.; Katlein, C.; Krumpen, T.; Bergmann, M.; Hehemann, L.; Gerdts, G. (2018) Arctic sea ice is an important temporal sink and means of transport for microplastic. Nature Commun. 9: 1505.

Pijogge, L.; Liboiron, M. (2021) Nunalinni kamatsianik palastikkinik igitauKattatunik Nunatsiavummi / Community-Based Monitoring of plastic pollution in Nunatsiavut, Northern Contaminants Program Annual Results Workshop (online presentation), 21 October 2021.

© The Author(s) or their Institution(s)

Pogojeva, M.; Zhdanov, I.; Berezina, A.; Lapenkov, A.; Kosmach, D.; Osadchiev, A.; Hanke, G.; Semiletov, I.; Yakushev, E. (2021) Distribution of floating marine macro-litter in relation to oceanographic characteristics in the Russian Arctic Seas. Mar. Pollut. Bull. 166: 112201.

Polasek, L.; Bering, J.; Kim, H.; Neitlich, P.; Pister, B.; Terwilliger, M.; Nicolato, K.; Turner, C.; Jones, T. (2017) Marine debris in five national parks in Alaska. Mar. Pollut. Bull. 117, 371-379.

Poon, F.E.; Provencher, J.F.; Mallory, M.L.; Braune, B.M.; Smith, P.A. (2017) Levels of ingested debris vary across species in Canadian Arctic seabirds. Mar. Pollut. Bull. 116, 517-520.

Primpke, S.; Lorenz, C., Rascher-Friesenhausen, R.; Gerdts, G. (2017) An automated approach for microplastics analysis using focal plane array (FPA) FTIR microscopy and image analysis. Anal. Methods 9, 1499–1511.

Primpke, S.; Booth, A.; Gerdts, G.; Gomiero, A.; Kögel, T.; Lusher, A.; Strand, J.; Scholz-Böttcher, B.M.; Galgani, F.; Provencher, J.; Aliani, S.; Pstankar, S.; Vorkamp, K. (2022) Monitoring of microplastic pollution in the Arctic: Recent developments in polymer identification, quality assurance and control (QA/QC), and data reporting. Arctic Sci. (this issue)

Provencher, J.F.; McEwan, M.; Mallory, M.L.; Braune, B.M.; Carpenter, J.; Harms, N.J.; Savard, G.; Gilchrist, H.G. (2013) How wildlife research can be used to promote wider community participation in the North. Arctic 66, 237-243.

Provencher, J.F.; Bond, A.L.; Avery-Gomm, S.; Borrelle, S.B.; Bravo Rebolledo, E.L.; Hammer, S.; Kühn, S.; Lavers, J.L.; Mallory, M.L.; Trevail, A.; van Franeker, J.A. (2017) Quantifying ingested debris in marine megafauna: a review and recommendations for standardatization. Anal. Methods 9, 1454-1469.

Provencher, J.F.; Avery-Gomm, S.; Liboiron, M.; Braune, B.M.; Macaulay, J.B.; Mallory, M.L.; Letcher, R.J. (2018) Are ingested plastics a vector of PCB contamination in northern fulmars from coastal Newfoundland and Labrador? Environ. Res. 167, 184-190.

Provencher, J.F.; Borrelle, S.B.; Bond, A.L.; Lavers, J.L.; van Franeker, J.A.; Kühn, S.; Hammer, S.; Avery-Gomm, S.; Mallory, M.L. (2019) Recommended best practices for plastic and litter ingestion studies in marine birds: Collection, processing, and reporting. FACETS 4, 111-130.

Provencher, J.; Kögel, T.; Lusher, A.; Vorkamp, K.; Gomiero, A.; Peeken, I.; Granberg, M.; Hammer, S.; Baak, J.; Larsen, J.R.; Farmen, E. (2022) An ecosystem-scale litter and microplastic monitoring plan under the Arctic Monitoring and Assessment Programme (AMAP). Arctic Sci. (this issue)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Rigét, F.; Vorkamp, K.; Bossi, R.; Sonne, C.; Letcher, R.J.; Dietz, R. (2016) Twenty years of monitoring of persistent organic pollutants in Greenland biota. A review. Environ. Pollut. 217, 114-123.

Rigét, F.F.; Bignert, A.; Braune, B.; Dam, M.; Dietz, R.; Evans, M.; Green, N.; Gunnlaugsdóttir, H.; Kucklick, J.; Letcher, R.; Muir, D.; Schuur, S.; Sonne, C.; Stern, G.; Tomy, G.; Vorkamp, K.; Wilson, S. (2019) Temporal trends of persistent organic pollutants in Arctic marine and freshwater biota. Sci. Total Environ. 649, 99-110.

Schang, G.; Robaire, B.; Hales, B.F. (2016) Organophosphate flame retardants act as endocrine-disrupting chemicals in MA-10 mouse tumor Leydic cells. Toxicol. Sci. 150, 499-509.

Seghers, J.; Stefaniak, E.A.; La Spina, R., Cella, C.; Mehn, D.; Gilliland, D.; Held, A.; Jacobsson, U.; Emteborg, H. (2021) Preparation of a reference material for microplastics in water – evaluation of homeneity. Anal. Bioanal. Chem. https://doi.org/10.1007/s00216-021-03198-7

Serra-Gonçalves, C., Lavers, J.L.; Bond, A.L. (2019) Global review of beach debris monitoring and future recommendations. Environ. Sci. Technol. 53, 12158-12167.

Shiklomanov, A.; Déry, S.; Tretiakov, M.; Yang, D.; Magritsky, D.; Georgiadi, A.; Tang, W. (2021) River freshwater flux to the Arctic Ocean. In: Yang, D.; Kane, D.L. (eds.) Arctic Hydrology, Permafrost and Ecosystems. Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-50930-9_24

Skjerdal, H.; Heldal, H.E.; Gwynn, J.; Strålberg, E.; Møller, B.; Liebig, P.L.; Sværen, I.; Rand, A.; Gäfvert, T.;. Haanes, H. (2017) Radioactivity in the marine environment 2012, 2013 and 2014. Results from the Norwegian National Monitoring Programme (RAME). StrålevernRapport 2017:13. Norwegian Radiation Protection Authority, Østerås, Norway. https://www2.dsa.no/publication/nrpa-report-2017-13-radioactivity-in-the-marine-environment-2012-2013-and-2014.pdf

Soltwedel, T.; Bauerfeind, E.; Bergmann, M.; Bracher, A.; Budaeva, N.; Busch, K.; Cherkasheva, A.; Fahl, K.; Grzelak, K.; Hasemann, C.; Jacob, M.; Kraft, A.; Lalande, C.; Metfies, K.; Nöthig, E.-M.; Meyer, K.; Quéric, N.-V.; Schewe, I.; Włodarska-Kowalczuk, M.; Klages. M. (2016) Ecol. Indic. 65, 89-102.

Strand, K.O.; Huserbråten, M.; Dagestad, K.-F.; Maurtizen, C.; Grøsvik, B.E.; Nogueira, L.A.; Melsom, A.; Röhrs, J. (2021) Potential sources of marine plastic from survey beaches in the Arctic and Northeast Atlantic. Sci. Total Environ.790, 148009.

Syberg, K.; Palmqvist, A.; Khan, F.R.; Strand, J.; Vollertsen, J.; Clausen, L.P.W.; Feld, L.; Hartmann, N.B.; Oturai, N.; Møller, S.; Nielsen, T.G.; Shashoua, Y.; Hansen, S.F. (2020) A nationwide assessment of plastic pollution in the Danish realm using citizen science. Sci. Rep. 10:17773.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Tanaka, K.; Takada, H.; Ikenaka, Y.; Nakayama, S. M. M.; Ishizuka, M. (2020) Occurrence and concentrations of chemical additives in plastic fragments on a beach on the island of Kauai, Hawaii. Mar. Poll. Bull. 150: 110732.

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

Tekman, M.B.; Wekerle, C.; Lorenz, C.; Primpke, S.; Hasemann, C.; Gerdts, G.; Bergmann, M. (2020) 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.

Tirelli, V.; Suaria, G.; Lusher, A.L. (2020) Microplastics in polar samples. In: Rocha-Santos et al. (eds). Handbook of Microplastics in the Environment. Springer Nature Switzerland AG, 2020.

Trevail, A.M.; Gabrielsen, G.W.; Kühn, S.; van Franeker, J.A. (2015) Elevated levels of ingested plastics in a high Arctic seabird, the northern fulmar *(Fulmarus glacialis)*. Polar Biol. 38, 975-981.

Tyack, P.L.; Miksis-Olds, J.; Ausubel, J.; Urban, E.R.Jr. (2021) Measuring ambient ocean sound during the COVID-19 pandemic. Eos 102. https://doi.org/10.1029/2021EO155447

UNEA (2022) End plastic pollution: Towards an international legally binding instrument. Draft resolution. United Nations Environment Assembly of the United Nations Environment Programme. Fifth session, Nairobi (hybrid), 22-26 February 2021 and 28 February – 2 March 2022, UNEP/EA.5/L.23/Rev

UNEP (2014) UNEP Year Book 2014: Emerging Issues in our Global Environment. United Nations Environment Programme, Nairobi, Kenya. ISBN 978-92-807-3381-5. https://wedocs.unep.org/handle/20.500.11822/9240

van der Meeren, G.; Prozorkevich, D. (eds.) (2021) Survey report from the joint Norwegian/Russian ecosystem survey in the Barents Sea and adjacent waters, August-November 2020. IMR/PINRO Joint Report Series. 1-2021, pp 123. https://www.hi.no/resources/BESS-2020_report-29_04_2021-Final-2.pdf

van Franeker, J.A.; Kühn, S.; Anker-Nilssen, T.; Edwards, E.W.J.; Gallien, F.; Guse, N.; Kakkonen, J.E.; Mallory, M.L.; Miles, W., Olsen, K.O.; Pedersen, J.; Provencher, J.; Roos, M.; Stienen, E.; Turner, D.M.; van Loon, W.M.G.M. (2021) New tools to evaluate plastic ingestion by northern fulmars applied to North Sea monitoring data 2002-2018. Mar. Pollut. Bull. 166, 112246.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

van Mourik, L.M.; Crum, S.; Martinez-Frances, E.; van Bavel, B.; Leslie, H.A.; de Boer, J.; Cofino, W.P. (2021) Results of WEPAL-QUASIMEME/NORMANs first global interlaboratory study on microplastics reveal urgent need for harmonization. Sci. Total Environ. 772, 145071.

van Sebille, E.; England, M.H.; Froyland, G. (2012) Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. Environ. Res. Lett. 7, 044040.

Vegter, A.C.; Barletta, M.; Beck, C.; Borrero, J.; Burton, H.; Campbell, M.L.; Costa, M.F.; Eriksen, M.; Eriksson, C.; Estrades, A.; Gilardi, K.V. (2014) Global research priorities to mitigate plastic pollution impacts on marine wildlife. Endanger. Species Res. 25, 225-247.

von Friesen, L.W.; Granberg, M.E.; Pavlova, O.; Magnusson, K.; Hassellöv, M.; Gabrielsen, G.W. (2020) Summer sea ice melt and wastewater are important local sources of microlitter to Svalbard waters. Environ. Int. 139, 105511.

Welden, N.A.C.; Lusher, A.L. (2017) Impacts of changing ocean circulation on the distribution of marine microplastic litter. Integr. Environ. Assess. Manag. 13, 483-387.

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

WHO (2019) Microplastics in drinking water. World Health Organization, Geneva, Switzerland. Licence CCBY-NC-SA3.0IGO

Wobus, F.; Shapiro, G.I.; Huthnance, J.M.; Maqueda, M.A.M. (2013) 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.

Wong, F.; Hung, H.; Dryfhout-Clark, H.; Aas, W.; Bohlin-Nizzetto, P.; Breivik, K.; Mastromonaco, M.N.; Brorström-Lundén, E.; Ólafsdóttir, K.; Sigurðsson, Á.; Vorkamp, K.; Bossi, R.; Skov, H.; Hakola, H.; Barresi, E.; Sverko, E.; Fellin, P.; Li, H.; Vlasenko, A.; Zapevalov, M.; Samsonov, D.; Wilson, S. (2021). Time trends of persistent organic pollutants (POPs) and chemicals of emerging Arctic Concern (CEAC) in Arctic air from 25 years of monitoring. Sci. Total Environ. 775, 145109.

Yakushev, E.; Gebruk, A.; Osadchiev, A.; Pakhomova, S.; Lusher, A.; Berezina, A.; van Bavel, B.; Vorozheikina, E.; Chernykh, D.; Kolbasova, G.; Razgon, I.; Semiletov, I. (2021) Microplastics distribution in the Eurasian Arctic is affected by Atlantic waters and Siberian rivers. Commun. Earth Environ. 2:23.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

Zettler, E.R.; Takada, H.; Monteleone, B.; Mallos, N.; Eriksen, M.; Amaral-Zettler, L.A. (2017) Incorporating citizen science to study plastics in the environment. Anal. Methods 9, 1392-1403.

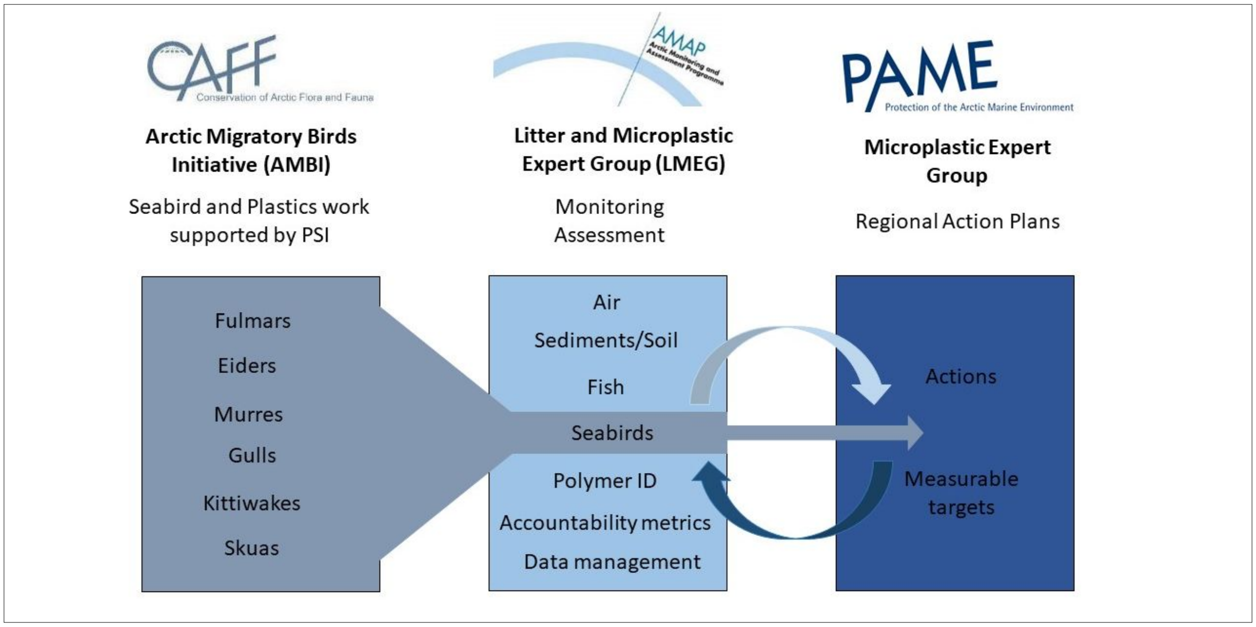

Figure 1 – Example of the cooperation and coordination on litter and microplastics work among three of the Arctic Council's Working Groups.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

© The Author(s) or their Institution(s)

Arctic Science Downloaded from cdnsciencepub.com by ALFRED-WEGENER-INSTITUT on 07/10/22
For personal use only. This Just-IN manuscript is the accepted manuscript prior to copy editing and page composition. It may differ from the final official version of record.

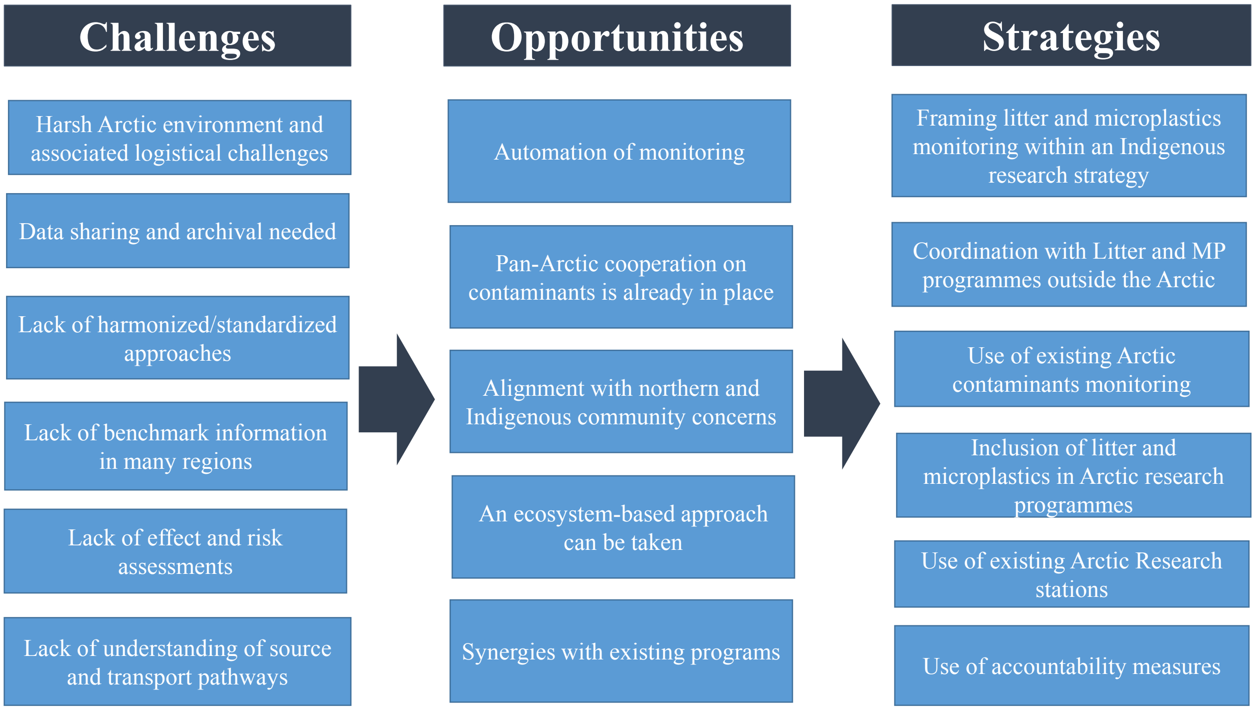

Figure 2: Summary of challenges, opportunities and strategies with regard to future monitoring of litter and microplastics in the Arctic.

© The Author(s) or their Institution(s)