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An ecosystem-scale litter and microplastics monitoring plan under the Arctic Monitoring and Assessment Programme (AMAP)

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Abstract

Lack of knowledge on levels and trends of litter and microplastics in the Arctic, is limiting our understanding of the sources, transport, fate, and effects is hampering global activities aimed at reducing litter and microplastics in the environment. To obtain a holistic view to managing litter and microplastics in the Arctic, we considered the current state of knowledge and methods for litter and microplastics monitoring in eleven environmental compartments representing the marine, freshwater, terrestrial, and atmospheric environments. Based on available harmonized methods, and existing data in the Arctic, we recommend prioritization of implementing litter and microplastics monitoring in the Arctic in four Priority 1 compartments—water, aquatic sediments, shorelines, and seabirds. One or several of these compartments should be monitored to provide benchmark data for litter and microplastics in the Arctic and, in the future, data on spatial and temporal trends. For the other environmental compartments, methods should be refined for future sources and surveillance monitoring, as well as monitoring of effects. Implementation of the monitoring activities should include community-based local components where possible. While organized as national and regional programs, monitoring of litter and microplastics in the Arctic should be coordinated, with a view to future pan-Arctic assessments.

Key words: Arctic, debris, spatial and temporal trends, baseline, monitoring

Résumé

Le manque de connaissances sur les niveaux et les tendances en matière de déchets et de microplastiques dans l'Arctique limite notre compréhension des sources, du transport, du devenir et des effets, et entrave les activités mondiales visant à réduire les déchets et les microplastiques dans l'environnement. Pour obtenir une vision globale de la gestion des déchets et des microplastiques dans l'Arctique, les auteurs ont examiné l'état actuel des connaissances et des méthodes de surveillance des déchets et des microplastiques dans onze compartiments environnementaux représentant les environnements marins, d'eau douce, terrestres et atmosphériques. À partir de méthodes harmonisées disponibles et des données existantes dans l'Arctique, ils recommandent de donner la priorité à la mise en œuvre de la surveillance des déchets et des microplastiques dans l'Arctique dans quatre compartiments de Priorité 1 : l'eau, les sédiments aquatiques, les rivages et les oiseaux marins. Un ou plusieurs de ces compartiments devraient être surveillés afin de fournir des données de référence sur les déchets et les microplastiques dans l'Arctique et, à l'avenir, des données sur les tendances spatiales et temporelles. Pour les autres compartiments environnementaux, les méthodes devraient être affinées pour les sources futures et la surveillance, ainsi que pour le suivi des effets. La mise en œuvre des activités de surveillance devrait inclure des composantes locales issues des communautés lorsque cela est possible. Bien qu'elle soit organisée sous la forme de programmes nationaux et régionaux, la surveillance des déchets et des microplastiques dans l'Arctique devrait être coordonnée, en vue de futures évaluations pan-arctiques. [Traduit par la Rédaction]

Mots-clés : Arctique, débris, tendances spatiales et temporelles, base de référence, surveillance

Introduction

Plastic pollution has been increasing globally over the last several decades (Rochman and Hoellein 2020), including in the Arctic (PAME 2019). The Fairbanks Declaration of the Arctic Council Ministerial noted, "(…) with concern the increasing accumulation of marine debris in the environment, its effects on the environment and its impact on Arctic communities." (Arctic Council 2017). The issue of plastic pollution in the Arctic was also raised in the Arctic Monitoring and Assessment Programme's (AMAP) recent assessment of *Chemicals of Emerging Arctic Concern* (AMAP 2017), and subsequently examined in the *Desktop Study on Marine Litter, including Microplastics in the Arctic* (PAME 2019) by the Protection of the Arctic Marine Environment (PAME) working group. These reports called for more work to address the transport, pathways, fate, and effects of plastic litter, and in particular to address microplastics in the Arctic marine environment. Although plastic pollution has become an issue of growing concern, leading to many local, regional, and international initiatives aiming to better understand and address it, limited information exists on the extent and development of plastic pollution in the Arctic (Halsband and Herzke 2019; Baak et al. 2020; Tirelli et al. 2020; Collard and Ask 2021).

Arctic ecosystems are currently undergoing rapid changes and experiencing multiple environmental stressors (Dietz et al. 2019; Jorgensen et al. 2019; Orr et al. 2020). For example, warming of the Arctic has led to a tremendous loss of multi-year sea ice affecting habitats and foraging of species across trophic levels (Frainer et al. 2017; 2021). Ocean acidification as a consequence of increased carbon dioxide in the ocean is also a concern for Arctic ecosystems (AMAP 2018). Additionally, the introduction of invasive species may affect Arctic ecosystems (Goldsmit et al. 2018). Many of the species in the region are of high cultural and nutritional importance for Indigenous and local communities, thus impacts on local ecosystems can have direct consequences for the well-being of Arctic residents (Underwood and Bertazzon 2020). Therefore, it is important to develop an understanding of the extent of plastic pollution as an additional stressor in Arctic ecosystems to broaden our understanding of cumulative effects in the region, to generate a stable basis for decision-making and to support regional action plans.

Monitoring the Arctic environment for the presence of litter and microplastics is necessary to understand and rank the extent and types of sources, transportation patterns, as well as the effects this group of pollutants may have on the ecosystems and organisms of this region. This knowledge can guide and provide information for decision-makers in planning and enforcing mitigation efforts (Levin et al. 2013). In the long run, monitoring data will be useful when evaluating the effectiveness of such mitigation actions. It has been demonstrated that litter and microplastics in the Arctic come from both local sources, and from outside the Arctic, via long-range transport (Bergmann et al. 2019; Halsband and Herzke 2019; Andrade et al. 2021). Therefore, it is important to align Arctic monitoring with global efforts, which will facilitate regional and global comparisons as well as coordinated actions (Bank et al. 2021). Building a monitoring plan at the ecosystem level, eventually including all major environmental compartments in the Arctic, i.e., marine, freshwater, terrestrial, and atmospheric, allows for a holistic approach discovering system interrelations and a better understanding of the fate and effects of plastic pollution (Bank and Hansson 2019).

For this reason, the ecosystem-scale Arctic monitoring plan should consider the existing regional and global monitoring programs and their protocols, including, but not limited to, the Marine Strategy Framework Directive (MSFD) of the European Union (EU), the Regional Sea Conventions (e.g., Oslo-Paris Commission for the Protection of the North-East Atlantic (OSPAR) and the Baltic Marine Environment Protection Commission; HELCOM). It is also important to consider programs across the polar regions, and thus monitoring in Antarctic waters (e.g., efforts under the Scientific Committee on Antarctic Research's (SCAR) Plastic Advisory Group). For many of the regional strategies and programs in the northern hemisphere, the Arctic is the common element between them, making monitoring in the Arctic critical to ensuring harmonization between regions and supporting harmonization in global efforts. Monitoring plastic pollution to reduce its effects in the environment also supports contributions to global regulation and effectiveness evaluation efforts (e.g., the United Nations Environmental Assembly (UNEA) and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP)), and the *UN Sustainable Development Goal* indicator 14.1.1b on plastic debris density.

Comprehensive monitoring of contaminants in biotic and abiotic environmental media is well established in the Arctic, and has been in place for several decades (AMAP 2017; Dietz et al. 2019; Rigét et al. 2019). These efforts are organized and implemented via national monitoring programs coordinated under the auspices of AMAP. AMAP provides a network for pan-Arctic cooperation, dialogue, and a platform for circumpolar assessments of levels and trends of pan-Arctic issues (e.g., climate change, ocean acidification, contaminants), which form the basis for policy recommendations to the Arctic Council (AMAP 2017; 2018). Thus, there is an opportunity to build on this previous work, and the established cooperative relationships, to develop a comprehensive, pan-Arctic litter and microplastics monitoring plan (AMAP 2021*b*).

The main purpose of this manuscript is to propose a holistic monitoring plan for litter and microplastics in the Arctic developed by AMAP's Litter and Microplastic Expert Group that will contribute to global efforts in tracking plastic pollution in the environment (AMAP 2021*b*). It presents a framework of key elements and considerations for a coordinated monitoring of litter and microplastics in the Arctic. It includes recommendations on environmental matrices and indicators, locations as well as times and frequency of sampling. The specific objectives are to:

I. promote a harmonized approach for baseline mapping across a wide range of environmental compartments in the Arctic that will enable a robust assessment of litter and microplastics pollution in the Arctic;
II. initiate monitoring programs for robust assessments of spatial and temporal trends;
III. provide guidance to Arctic States, Permanent Participants (Indigenous peoples' organizations), and the Arctic Council Observers for national monitoring initiatives, community-based programs, and other mechanisms in the context of a pan-Arctic program;
IV. act as a catalyst for future work in the field of litter and microplastics pollution in the Arctic; and
V. enhance the ability of the Arctic Council to assess the state of the Arctic region with respect to plastic pollution and to contribute with Arctic regional data and information for future assessments on a broader international scale to the Arctic Council.

Definitions of litter and microplastics

The definitions of litter and microplastics have varied over time and continue to be refined and revised as work proceeds. For discussion within this manuscript, the terms *litter and microplastics* are used as follows:

- *Litter* is used to describe any object that is persistent, manufactured or processed solid material abandoned, lost, or discarded in the environment. This may include plastic, machined wood, textiles, metal, glass, ceramics, rubber, and other persistent man-made materials. These products often are worn down over time, but do not entirely biodegrade for a long time, and are therefore persistent in the environment. This is consistent with the US's National Oceanic and Atmosphere Administration's (NOAA) definition of marine debris, OSPAR's marine litter definition, and is also used by PAME.
- *Microplastics* include synthetic polymers, such as polyethylene and polystyrene including co-polymers and elastomers, as well as application-wise comparable anthropogenic particles that cannot in all contexts be strictly defined as plastics, such as semisynthetics, co-polymers, acrylic paints, rubber, silicones, and tire abrasion rubber-blend particles. Thus, *microplastics* can be harmonized with microlitter for methods and reporting purposes because the methods targeting microplastics yield results on a wide range of anthropogenic particles and cannot always be assigned to an unambiguous identification. This is consistent with the definitions of the EU MSFD (Directive 2008/56/EC).
- For *particle size*, the use of the term "litter and microplastics" is specifically designed to encompass all the size classes found in the environment. This is consistent with the EU MSFD by defining microlitter particles as <5 mm, without a lower size limit definition in the Commission Decision 2017/848/EU. In the practical work with microplastics analysis, operationally defined size classes above and below 1 mm are often used (Table 1). By this definition, nanoplastics would be a subgroup of microplastics. Recently, a specific definition has been put forward for nanoplastics, defining a material with an external dimension in the nanoscale (0.001–0.1 μm) or having internal or surface structure in the nanoscale (European Commission 2022). In this article, nanoplastics are conceptually encompassed by microplastics, but, given the technical challenges in their determination, not currently considered for environmental monitoring in the Arctic.

Table 1. Size classes of plastic particles that are typically, although not exclusively, reported in the eleven Arctic environmental compartments assessed in the development of the monitoring plan.

Environmental compartment	Particles >1 mm	Particles < 1 mm
Atmospheric deposition		X
Snow/ice		X
Water (freshwater and marine)	X	X
Aquatic sediments	X	X
Terrestrial soil	X	X
Shorelines	X	
Seabed	X	
Invertebrates		X
Fish	X	X
Seabirds	X	
Mammals	X	X

Note: We used 1 mm as cut-off value here based on common approaches.

Types of monitoring

There are several different types of monitoring, which can complement one another in the sense that the same observation and sampling strategy can be applied for different purposes. It is important to recognize that monitoring activities can be led and implemented by a variety of partners including researchers and community groups (i.e., northern and Indigenous communities).

- **Baseline mapping**: Monitoring actions to establish the benchmark levels for specific areas at a given time, which can be a starting point for studying spatial and temporal trends. Although the true environmental background level of litter and microplastics in the environment is zero, the term benchmark level is used to describe the most historic state of litter and microplastics in the environment.
- **Trend monitoring**: Monitoring actions designed to detect changes across temporal and (or) spatial scales.
- **Source and surveillance monitoring**: Monitoring actions to monitor potential point sources or specific pressures, including monitoring for determining local sources (e.g.,

melting sea ice, rivers, dumping sites, wastewater outlets, etc.), or the transportation of litter and microplastics into the Arctic via long-range transport (e.g., by air, ocean currents, transport by biota).
- **Compliance monitoring**: Monitoring of environmental parameters to ensure that regulatory requirements/standards are being met.
- **Effect monitoring:** Monitoring of environmental parameters that are sentinels for effects caused by plastic pollution and related contaminants that affect biota.
- **Risk-based monitoring**: Monitoring actions aim to assess the status of contamination levels critical for certain species, populations, human health, or food safety.

This monitoring plan focuses on baseline mapping, trend monitoring, and source and surveillance monitoring for litter and microplastics. Other types of monitoring are discussed in other articles within this Collection . For example, potential future effect monitoring is discussed for fish (Kögel et al. In press) and birds and mammals (Lusher et al. 2022). Additionally, source and surveillance monitoring is discussed more specifically in the articles focusing on shorelines (J. Strand and P. Murphy, personal communication, 2022), water and sediments (Martin et al. 2022), and terrestrial soils (J.C. Vermaire, M.P.T. Bourdages, and A. Lusher, personal communication, 2022). General considerations on challenges, opportunities, and strategies for future monitoring efforts are discussed by Provencher et al. (2022), also found in this Collection.

There are a range of other considerations when selecting monitoring tools for a large region such as the pan-Arctic. This includes how susceptible and vulnerable compartments are to accumulating plastic pollution, as well as how sensitive measures of compartments are to changes in environmental levels. For biota there are additional considerations for how lethal sampling may affect population levels and species management, and how protected species may or may not be used as bioindicators for pollution monitoring (discussed more in Lusher et al. 2022). Accessibility is an important question in the Arctic as it is a diverse landscape, and must factor into any pan-Arctic monitoring discussion to ensure that monitoring recommendations can be carried out across a large portion of the target area. Many monitoring efforts also target hotspots of contamination or change to evaluate potential fate and effects questions.

At the beginning of any monitoring endeavour, it is important to establish a benchmark level at selected sites that can be monitored regularly. The results of subsequent surveys can be compared with the benchmark levels to see whether there has been a change in quantities, perhaps as the result of policy interventions, or because of an event (e.g., storm event or large-scale spill of litter or plastics). Over time, this can result in systematic trend monitoring. Due to the inherent variability in the abundance of litter and microplastics in all environmental compartments, high numbers of replicates and several years of sampling or observations may be required to detect a temporal trend with sufficient statistical power. The inherent variability—and resulting statistical power—must be considered in the sampling strategy, regarding sampling volumes and frequencies. Improving the knowledge of such variability is an area of ongoing research. Therefore, in the absence of consolidated knowledge on variability, annual (i.e., seabirds) or seasonal (i.e., sediments, water, and shorelines) monitoring is recommended for the **Priority 1** compartments (described below) across the pan-Arctic, whereas the frequency of monitoring in other compartments could be more flexible, depending on the questions to be addressed. As with all monitoring efforts, variability and the statistical power of the time series to detect significant changes should be continually assessed and monitoring intervals adapted.

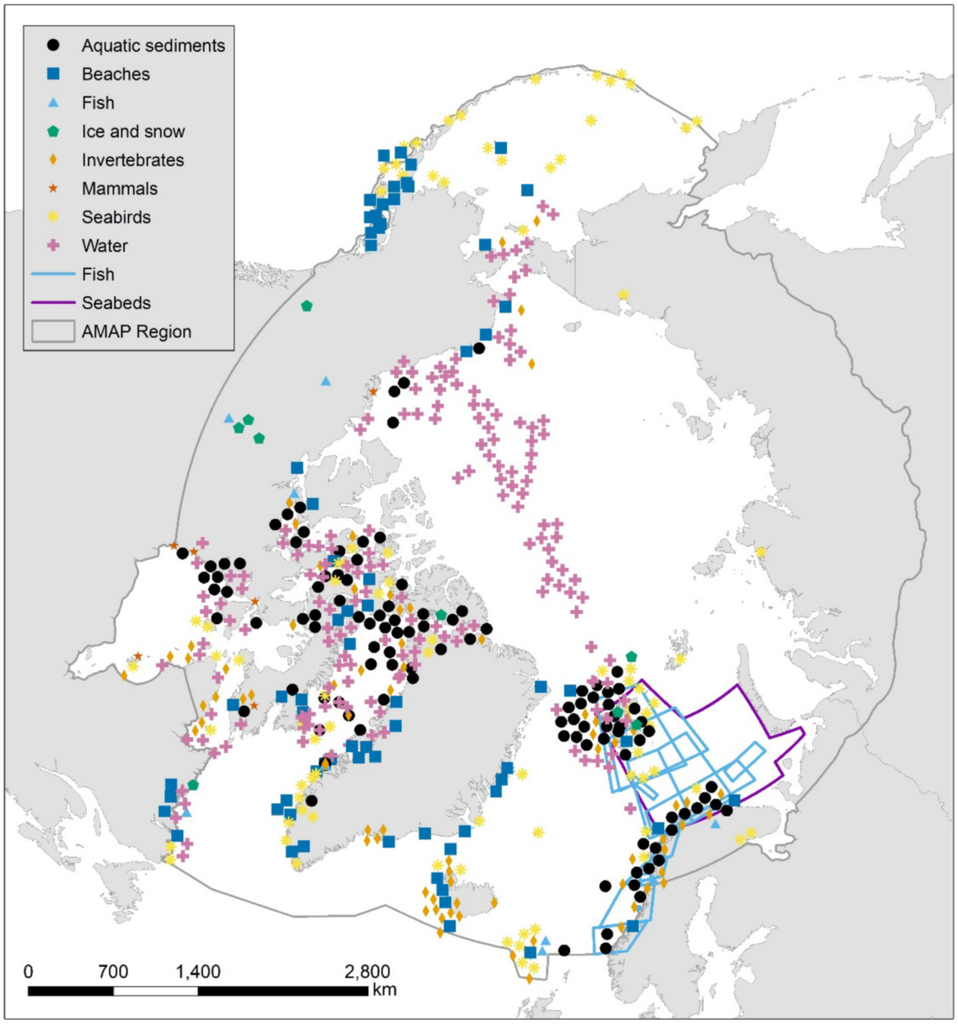
Recommendations for baseline mapping and time trend monitoring

To develop a holistic ecosystem approach for the pan-Arctic monitoring plan, several environmental matrices were assessed with regard to their suitability for baseline mapping, trend monitoring, and source and surveillance monitoring of litter and microplastics. This was based both on aspects of science and feasibility. The following eleven environmental indicators were considered for the monitoring plan (AMAP 2021*b*), representing the aquatic, terrestrial, and atmospheric compartments: shorelines, water, aquatic sediments, terrestrial soils, atmospheric deposition, snow/ice, seabed, invertebrates, fish, seabirds, and marine mammals (Table 1; Fig. 1). We recognize that there are other relevant environmental compartments in the Arctic (e.g., deep sea corals, terrestrial invertebrates) and future work is needed to understand how litter and microplastics may accumulate in and affect these compartments as well. The eleven compartments examined are complementary regarding the main size classes of litter and microplastics in the environment (Table 1), and thus represent a suite of compartments that can be used to track plastic pollution over a spectrum of particle sizes. The reason for the 1 mm cut-off in Table 1 relates to a combination of the status of method development, feasibility, and physiological features, which are explained in more detail in the other publications in this Collection (Primpke et al. 2022).

To be considered a **Priority 1 recommended monitoring compartment**, the following criteria needed to be met, which are critical for widespread and immediate implementation:

1) litter and (or) microplastics are known to be present in these compartments;
2) standardized or harmonized protocols have been developed and implemented in several regions (e.g., seabirds within OSPAR, shorelines within OSPAR and NOAA);
3) data are currently available in several Arctic regions;
4) sampling (i.e., collection method or species) can be implemented across most of the Arctic without additional need for infrastructure or technology development (Fig. 2);
5) approaches can be aligned with litter and microplastics monitoring outside the Arctic, ensuring that Arctic data can be used in future broader international or global assessments; and

Fig. 1. Examples of the types and locations of existing data on litter and microplastics in the AMAP region. Data are from country submitted reports, as well as the peer-reviewed literature. Points are jittered to prevent overlap and make the symbols visible to demonstrate the spread of the data. Data points are from AMAP (2021*b*). The projection is the North Pole Lambert Azimuthal Equal Area, and the AMAP border is from https://www.amap.no/work-area/document/868.



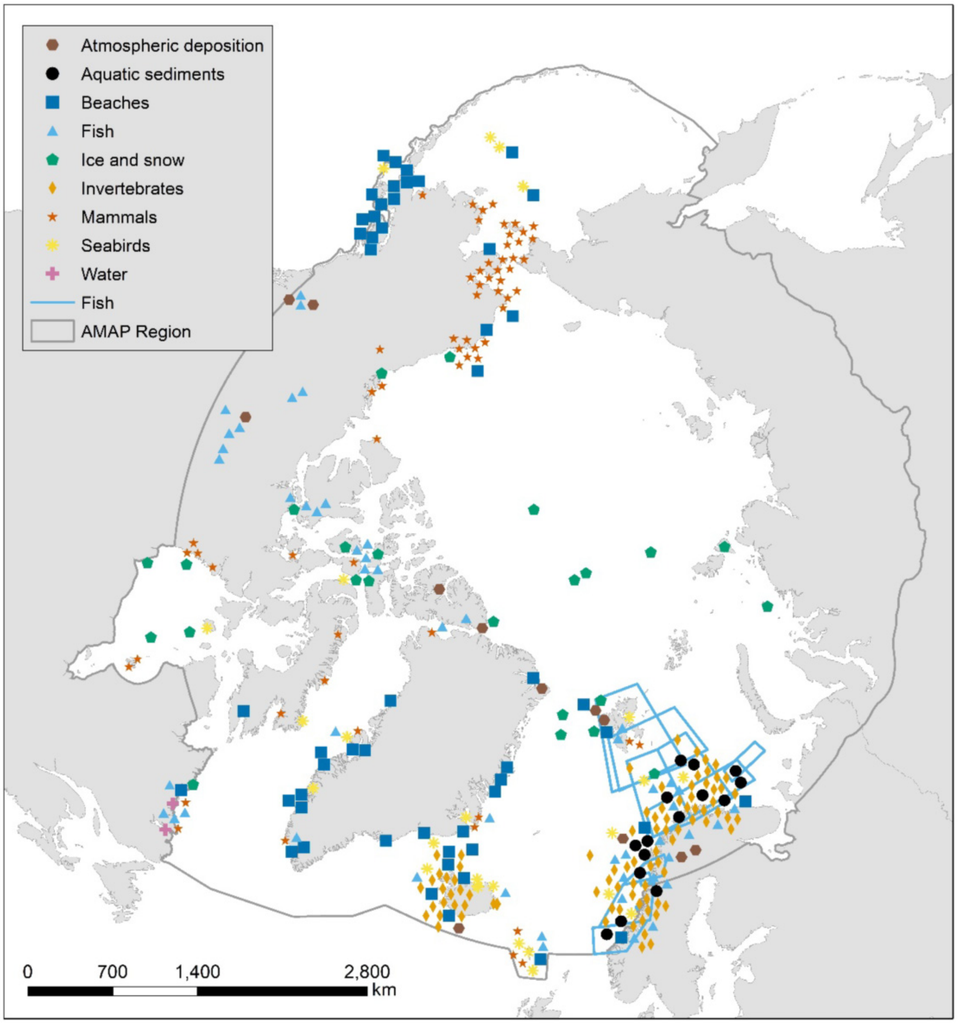
6) future sampling can be carried out in collaboration with existing programs (Fig. 2).

Priority 1: monitoring compartment recommendations for the pan-Arctic region

Using the criteria outlined above we identified Priority 1 compartment recommendations as those where monitoring should be implemented, when possible and where relevant, immediately, across all regions in the pan-Arctic. The Priority 1 recommendations include monitoring indicators of water (freshwater and marine), sediments (freshwater and marine), shorelines, and seabirds (Table 2). Specifically, these recommendations include measuring microplastics in surface water using nets or pumps in inshore waters and pumps in offshore waters, microplastics in sediments (including freshwater inputs, estuaries, and marine zones), litter surveys on shorelines, and plastic ingestion in northern fulmars (Table 2).

In addition to the criteria outlined above for the selection of Priority 1 monitoring, it should be noted that the combination of water, sediments, shoreline, and seabird monitoring covers a range of size classes of litter and microplastics (Table 1). Sampling from sediment and water samples commonly produces data for size classes varying between 100 μm (but some as low as 10 μm) and 1 mm and above, typically defined by the selected methodology, i.e., mesh and filter sizes (Martin et al. 2022). Thus, water sampling often uses nets of 300 μm mesh size. Seabirds, specifically those that feed in the open ocean, can be used to study litter particles between 1 and 25 mm (Baak et al. 2020). Shoreline surveys focus mostly on litter, and largely on pieces >25 mm (J. Strand and P. Murphy, personal communication, 2022). Thus, combining these compartments yields information on an overlapping and wide range of litter and microplastics (Table 1).

Fig. 2. Locations of current monitoring stations for chemical contaminants (air/atmospheric deposition, ice and snow, invertebrates, fish, birds, mammals, sediments, and water), litter (via beaches), and populations (seabirds, fish, and mammals), representing the environmental compartments of the monitoring plan (AMAP 2021*b*). Points are jittered to prevent overlap and make the symbols visible to demonstrate the spread of the data. Data points are from AMAP (2021*b*). The projection is the North Pole Lambert Azimuthal Equal Area, and the AMAP border is from https://www.amap.no/work-area/document/868.



This combination of Priority 1 compartments allows for a flexibility in approaches for regional implementation in different parts of the Arctic that will still result in data that can be compared at the pan-Arctic level. Different Priority 1 compartments may be targeted based on locally or nationally different priorities, including the monitoring of different size classes of litter and microplastic, or of specific matrices or species. For example, if larger size classes of plastic (>1 mm) are the main interest in a specific setting, then shoreline surveys and seabirds (i.e., northern fulmars) should be prioritized for monitoring efforts. If smaller size classes of plastic pollution (<1 mm) are of concern, water and sediment sampling should be prioritized over the other compartments.

We also recommend that monitoring programs consider a joint water and sediment approach, where possible. The rationale for this recommendation is that water and sediment sampling can often be carried out in the same sampling campaign and provide complementary, but not redundant, information on the status and trends of plastic contamination—including potential exposure of organisms inhabiting different ecological niches, from the pelagic to the benthic habitats. Furthermore, water and sediment sampling provide different spatial and temporal perspectives on plastic pollution. Sediments provide a more integrated signal of plastic contamination and are considered a major sink. In contrast, water samples will reflect more rapid fluctuations, for example caused by increased ship traffic, storm events, ice cover, or wastewater treatment alterations. Water currents can also carry buoyant particles long distances and therefore may not be reflective of local pollution sources. This is discussed further by Martin et al. (2022) in this Collection.

Priority 2: monitoring recommendations

Given that some countries may wish to explore litter and microplastics monitoring in additional environmental com-

Table 2. Summary of the Priority 1 compartment recommendations for monitoring of litter and microplastics in the Arctic.

Environmental compartment	Monitoring details
Shorelines (J. Strand and P. Murphy, personal communication, 2022)	Shoreline surveys focus on litter and can be performed by a variety of groups, provided that a harmonized approach and standardized reporting methods are used. Given that some of the most abundant litter items in several Arctic regions are abandoned, lost or otherwise discarded fishing gear (ALDFG), implementing widespread shoreline monitoring for litter will improve the assessment of the current extent of pollution, identify hotspots, and inform mitigation actions with regard to ALDFG in particular. Surveys should be carried out at least once during the ice-free seasons, and along a variety of shoreline types to understand how litter may be distributed along coastlines. OSPAR and NOAA have ongoing shoreline litter monitoring programs with existing protocols, and comparability of the data produced by these programs should be ensured.
Water (surface) (Martin et al. 2022)	Water sampling can be performed using harmonized methods and standard reporting, via existing monitoring programs. Water sampling can include litter and microplastics by implementing different methodologies. Water samples in inshore regions can be carried out using nets or pumps with 300 μm mesh size, typically from 1 to 7 m below the surface. When pumping, the use of sequential filters with decreasing mesh sizes, e.g., 1 mm, 300 μm, 100 μm, 20 μm is useful. Lower size classes can provide additional data and should be assessed when possible. Sample volumes will depend on local sampling conditions. Sampling in rivers and estuarine ecosystems, particularly in regions of sewage outlets should be included for source monitoring, i.e., establishing baseline levels of litter and microplastics across the Arctic entering via riverine and more localized inputs (e.g., sewage output). Frequency of sampling could be seasonal or annual but needs to be considered in the context of local water movement patterns.
Aquatic sediments (Martin et al. 2022)	Sampling of aquatic and shoreline sediments primarily focuses on microplastics. A variety of plastics including different types of polymers, shapes and sizes of microplastics can be found in sediment samples, from beaches to the sublittoral zone. Sampling across sediment types can provide information on the movements and sinks of microplastics in aquatic systems. It also allows for the detection of particles with changed density or settling properties resulting from biofouling. Microplastics in sediments should be monitored and reported in size categories 300 μm–1 mm and 1–5 mm. Lower size classes can provide additional information and should be assessed when possible. Sediment monitoring near rivers and estuarine ecosystems and sewage/wastewater outlets can improve the understanding of historic and current sources and levels of deposition. Sediment sampling on shorelines in conjunction with shoreline litter monitoring can also address questions about the source and fate of plastic pollution in coastal ecosystems.
Seabirds (Lusher et al. 2022)	Several species of seabirds have been assessed for ingestion of litter > 1 mm, as well as for entanglement over several decades. Nest incorporation data can provide information on larger particles and litter. Data show that microplastics accumulated in seabird stomachs can vary in size depending on the feeding mode of the specific species, season, as well as other biological factors, therefore species ecology is important for interpreting results. Northern fulmars should be focused on as a primary species through harvested birds, bycatch specimens, or beached birds. Fulmars are recognized as a bioindicator of plastic pollution in, e.g., OSPAR because fulmars directly ingest plastic at the surface of the water and accumulate plastics in their stomachs. Future work could be extended to other species across the Arctic, and to smaller particles as well, based on proper procedures. Although the use of seabirds as samplers of litter and microplastics is limited in some regions due to the species abundance or because of the conservation status of the species, it provides an important connection to the plastic monitoring in OSPAR.

partments because of regionally or locally specific questions, data gaps, or because they are transitioning from research to monitoring, we also present several **Priority 2 recommended monitoring compartments** (Table 3). These Priority 2 recommendations include compartments where further research is needed before they can be widely implemented for harmonized monitoring approaches. The criteria that distinguish these compartments from the Priority 1 compartment recommendations include:

1) (standardized) comparable or harmonized protocols are in place, but need to be further refined through implementation and a greater community of practice;
2) data may not be available in most regions of the Arctic, but the compartments can now be widely sampled with coordinated efforts;
3) program development in some regions is needed to ensure greater geographical coverage of the Arctic; and
4) additional monitoring efforts will support developments in infrastructure or technologies.

Using these criteria, the Priority 2 compartment recommendations include indicators for air (atmospheric deposition), invertebrates, and fish (Table 3). The goal in the coming years should be to further develop the techniques and capacities for these media that would allow their use in harmonized monitoring approaches in the Arctic, so they can also be considered for baseline mapping and future trend monitoring. Each compartment in the Priority 2 recommendations may include more than one indicator, for example different invertebrate and fish species (Table 3). The choice of specific indicators should balance the local and regional monitoring questions and the wish for harmonization across the Arctic.

Priority 3: currently no monitoring recommendations

Several compartments in the Arctic such as snow/ice, seabeds, terrestrial soils, and mammals are currently still in the exploratory phase with regard to systematic measurements of litter and microplastics. Current studies are often

Table 3. Summary of the Priority 2 recommendations for monitoring of litter and microplastics in the Arctic.

Environmental compartment	Monitoring details
Air via atmospheric deposition (Hamilton et al. In press)	Sampling of microplastics in air can be based on atmospheric deposition using existing infrastructure and sampling efforts in several regions of the Arctic (i.e., the existing atmospheric monitoring stations in the Arctic; Wong et al. 2021). Studies in urban areas at temperate latitudes have shown airborne plastic pollution (e.g., Dris et al. 2016), but there is little information from remote regions to assess the long-range atmospheric transport of microplastics. Microplastics that are likely subjected to atmospheric transport are mainly <300 μm and consist of mostly microfibers. Plastic particles as small as 10 μm can be detected in atmospheric deposition samples.
Invertebrates (Grøsvik et al. In press)	Most invertebrates have demonstrated a capacity to ingest microplastics, but current knowledge on microplastics in Arctic invertebrates is limited. Studies show that microplastics detected in invertebrates vary in densities and size depending on the feeding mode of the species examined. It is critical to have detailed knowledge of the ecology and feeding behaviour of the sampled species to correctly interpret microplastic data. It is also important to have insight into particle feeding dynamics in the specific species under the specific sampling conditions, because feeding rates and particle selectivity are highly circumstantial. Analyzing a range of different invertebrate species can lead to a better understanding of the fate of microplastics in the benthic and pelagic environments, as well as answer questions related to trophic transfer and inform effect studies. The choice of species should also consider human consumer health considerations and levels in invertebrates should be related to critical levels for human ingestion.
Fish (Kögel et al. In press)	Studies on microplastic accumulation in fish from the Arctic region show highly variable results with relatively low incidence compared to other taxa. However, most studies only investigated the fish stomach content for plastic larger than 500 μm, whereas new studies show occurrence of plastic below that size in guts/gastrointestinal tissues, fillet, and liver. Several species of fish are regularly sampled throughout much of the Arctic for various purposes, including chemical contaminant studies and stock assessments. The existing programs could be adapted for synergy to include microplastic studies. Different fish species can provide information on microplastic in the benthic and pelagic environments. This can result in data on microplastics of varying densities and size classes given that fish have different types of feeding habits. Thus, as with other species, it is critical to have a detailed knowledge about the feeding behaviour of the sampled species to correctly interpret microplastic data. Sampling of selected fish tissues can also provide information needed for questions relating to effects on Arctic ecosystems and human exposure when combined with the assessment of the condition of the organisms and critical levels for human ingestion.

widespread and limited to few locations, thus, a pan-Arctic approach is currently not possible. We also classify these compartments as Priority 3 because we lack basic understanding of what the data represent as well as basic methodological techniques for sample treatment in the field and in the laboratory. Thus, we do not consider monitoring in these compartments as sufficiently developed to provide the data needed for different types of monitoring. However, they still have the potential for source and surveillance monitoring, and should be considered in the context of this type of monitoring plan currently in development. Additionally, as sampling and measurement techniques continue to be developed, these compartments should be re-assessed as for their use across the pan-Arctic.

Recommendations for source and surveillance monitoring

In addition to baseline and trend monitoring there is a need to identify sources of litter and microplastics to the Arctic and to assess the effectiveness of mitigation actions and other measures, such as those listed in the *Regional Action Plan on Marine Litter in the Arctic* (PAME 2021). Baseline mapping followed by trend monitoring will support such assessments, but more focused efforts around potential sources of litter and microplastics will be needed, including monitoring point sources and accidental spills. The monitoring frequency should consider potential seasonal and interannual patterns (Table 4).

As discussed in the *Regional Action Plan on Marine Litter in the Arctic* (PAME 2021), a suite of monitoring tools are recommended that can be used to track the effectiveness of the actions. Many actions relate to abandoned, lost or otherwise discarded fishing gear because this is a large component of the litter on many Arctic coastlines. For these actions, monitoring the seabed and shorelines for litter is recommended. For actions that are examining the sources of plastic pollution via waste and wastewater handling, depending on the location, shorelines, freshwater, terrestrial soils, seawater, sediments, and marine birds via gull boluses should be considered. Regardless of the potential source, a specific location-based approach should be taken to tailor the monitoring strategy to the specific question and local conditions, including natural phenomena, such as major water exchange events. In general, upstream monitoring, i.e., measuring as close to a source as possible, will increase the chance of detecting changes both in quantity and composition of microplastic pollution. The link between environmental pollution and relevant actions also becomes stronger.

Implementation of the monitoring plan

While we present a plan for pan-Arctic monitoring of litter and microplastics, the implementation of such monitoring is the responsibility of national and regional governments. Long-term monitoring efforts fall under the governance of a variety of mechanisms across the Arctic, with litter and microplastics typically considered by groups also dealing with

Table 4. Summary of source and surveillance monitoring that may be undertaken in environmental compartments for litter and microplastics.

Environmental compartment	Recommendation summary for source and surveillance monitoring
Air via atmospheric deposition (Hamilton et al. In press)	Local samples around point sources can be used to detect microplastics in relation to emissions into air and implemented actions. More widespread and remote sampling can document which type of microplastic is deposited on the larger scale by long-range transport including remobilization processes. This information will also be useful for creating Arctic specific circulation models.
Snow/ice (Hamilton et al. In press)	Local samples around point sources can be used to detect microplastics in relation to, e.g., specific waste management tools and implemented actions. More widespread sampling can document how litter and microplastics are deposited and transported at the larger scale. This information will also be useful for creating Arctic specific circulation models.
Water (Martin et al. 2022)	Sampling of both fresh- and seawater can be used to track sources of litter entering the Arctic aquatic environment. It can be difficult to target the specific site in which microplastics originating from a land-based source will concentrate; therefore, an understanding of local currents is needed. The best location for sampling is close to the entry point, whether the source is an effluent or an ice front. The interfaces land–water and ice–water are important to target.
Sediments (Martin et al. 2022)	Sampling of sediments at the littoral and the subtidal zones can be a useful tool for surveillance monitoring of litter and microplastics. It can be difficult to target the specific site at which microplastics originating from a land-based source will settle; therefore, an understanding of local hydrodynamics is needed. Paired with beach surveys for litter, marine sediments can reflect how local sources influence microplastic levels and types in the surrounding areas.
Terrestrial soils (J.C. Vermaire, M.P.T. Bourdages, and A. Lusher, personal communication, 2022)	Although terrestrial soil sampling is not often considered in addressing marine litter and microplastics, in many regions the largest source of marine litter and microplastics is land-based. Monitoring terrestrial soils for microplastics can inform on how microplastics move from the land to the marine environment, and how this may be altered under different management scenarios. This will be particularly relevant in relation to climate change-related melting of permafrost, e.g., under landfills or from atmospheric deposition.
Seabed (B.E. Grøsvik, L. Buhl-Mortensen, and A.M. Booth, personal communication, 2022)	Seabed surveys for litter can serve as a useful tool to track sources of litter. This type of monitoring should be employed in regions where ALDFG may be concentrated.
Shorelines (J. Strand and P. Murphy, personal communication, 2022)	Shoreline surveys for litter are likely to be one of the main tools for surveillance monitoring of litter. Paired with marine sediment monitoring for microplastics and accountability methods, beach surveys can indicate sources of pollution. Areas susceptible to ALDFG accumulation and close to landfills should be considered for this type of monitoring.
Invertebrates (Grøsvik et al. In press)	Invertebrates with known ecology and functional group identity can be used around local sites to examine how microplastics enter the biological compartments and food chains. Links to human risk through seafood consumption can be established.
Fish (Kögel et al. In press)	Litter and microplastic assessments in fish with known ecology and migration patterns, or in landlocked species, can provide information on local sources of pollution and human risk through consumption.
Seabirds (Lusher et al. 2022)	Bird species that regurgitate (i.e., gulls, skuas) can be used to track local sources of litter and microplastics because these samples are nonlethal to the investigated birds and reflect their diet during the hours before collection. Nest incorporation of litter by black-legged kittiwakes can also be used to study local sources of litter and can be tracked over time easily via community-based monitoring.
Mammals (Lusher et al. 2022)	Both terrestrial and marine mammals can be used to understand the sources and effects of litter through the identification of plastic entanglement and ingestion. In case of mammals that ingest or are entangled in plastic pieces, these items are usually sufficiently large and intact often allow for source identification.

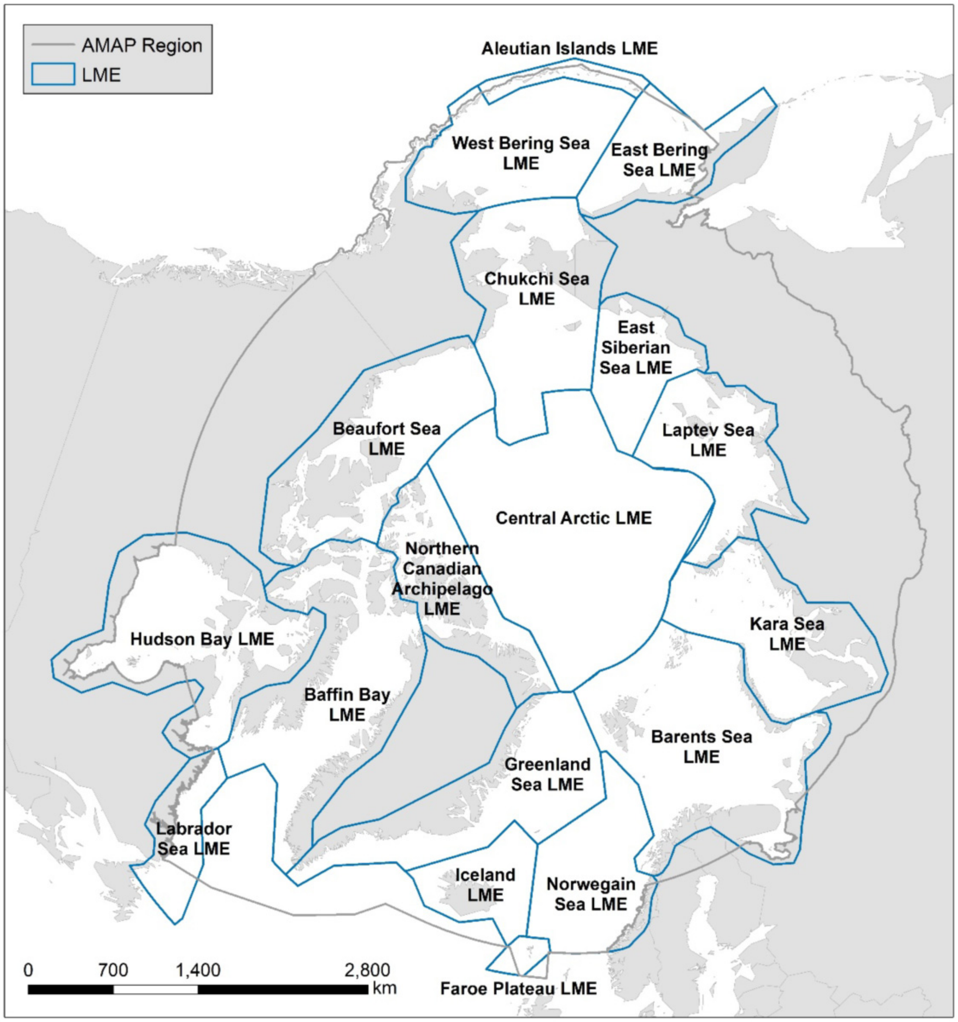
contaminants monitoring. Results from nationally or regionally governed monitoring program are typically assessed in a circumpolar context by AMAP.

We recommend that Arctic countries should consider implementation of monitoring in the most relevant compartments within the selected large marine ecosystems under their jurisdiction (Fig. 3). This will allow for future spatial trend monitoring across large-scale areas that experience similar oceanographic conditions (Fig. 4).

Monitoring programs can be implemented in a variety of ways, including nationally led and community based. Monitoring programs often involve infrastructure for observations and sampling, e.g., research stations and observatories, but increasingly include community-based and crowdsourced science initiatives for locally organized sampling campaigns or large-scale collections of observations reported via online platforms. Monitoring under the auspices of AMAP is usually initiated nationally or regionally and implemented locally, typically in collaboration with local and Indigenous communities, where applicable. Sampling strategies can include species-specific and opportunistic (sampling what is feasible to catch) sampling, and a combination of both. The engagement with partners is important to ensure that locally relevant questions are addressed, and that local expertise is included. Provencher et al. (2022) in this Collection present a more detailed discussion on examples of how existing monitoring programs can be expanded to include litter and microplastics.

It is also recommended that sampling for litter and microplastics be implemented into existing monitoring efforts

Fig. 3. The large marine ecosystems (LMEs) within the AMAP boundary. It is recommended that the Priority 1 recommendations for monitoring litter and microplastics are implemented in at least one location across all the Arctic LMEs where possible. The projection is the North Pole Lambert Azimuthal Equal Area.

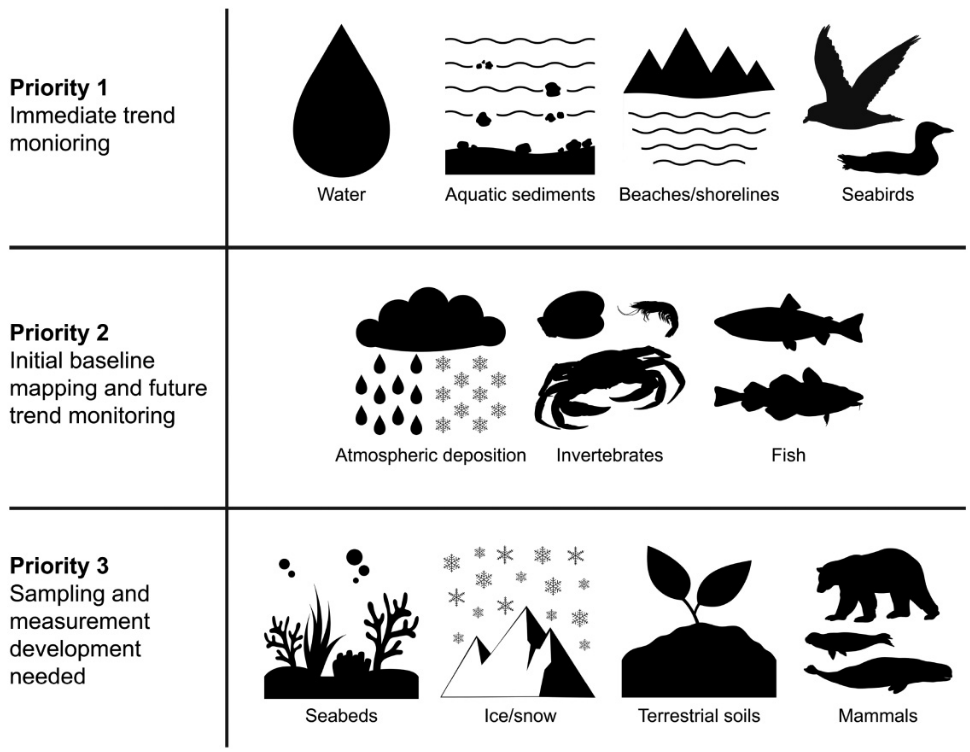


in the Arctic, for example programs targeting chemical contaminants (Fig. 2). One example of implementing litter and microplastics monitoring via existing chemical contaminants programs is the examination of seabirds and seals for ingested microplastics in Northern Canada. Both seabirds and seals are regularly collected by Inuit communities for contaminant analysis under the Northern Contaminants Program (Braune et al. 2014; Houde et al. 2020), and since 2007 stomach samples from the same individuals collected for contaminants research have also been examined for microplastics (Baak et al. 2020; Bourdages et al. 2020).

There are, furthermore, more than 100 research stations and observatories located in the Arctic, some of which are designed to be permanent or semipermanent. These stations can provide important support to litter and microplastics monitoring projects, especially in understudied environmental compartments (i.e., terrestrial soils). One example of how these research stations can contribute to litter and microplastics monitoring is demonstrated by the work at the long-term ecological research observatory HAUSGARTEN, established by the Alfred Wegener Institute (Germany). Since 2002, the HAUSGARTEN observatory in the Arctic has conducted marine plastic monitoring on the seafloor using towed seafloor photography (Bergmann and Klages 2012; Tekman et al. 2017).

Community-based monitoring includes projects that are created, led, and carried out by community groups. Monitoring projects may also include projects that are co-developed with communities, and projects that are created and facilitated by outside principal investigators but led and carried out by communities. The main benefits of these programs are that they concretely address community concerns about plastics and tend to focus on local needs, methods, and goals, as recommended by the recent National Inuit Research Strategy (ITK 2018). An example of a community-based project is “Community Monitoring of Plastic Pollution in Wild Food and Environments in Nunatsiavut”, a project of the Inuit Nunatsiavut Government, funded by Canada’s Northern Contaminants Program (Pijogge and Liboiron 2021). The program focuses on plastic pollution in traditional food webs and cul-

Fig. 4. Overview of the environmental compartments recommended for monitoring of litter and microplastics in the Arctic.



turally important ecosystems for Inuit hunters and fishers and employs local Inuit to carry out research on their own land.

Research projects that engage a broad section of the community (civic science, citizen science, or crowdsourced science) could also be employed in establishing litter and microplastic monitoring. This entails the collection of scientific information and observations carried out by the general public, often as part of a collaborative project led by a team of researchers that establish the methods and analyze the data. These efforts are usually opportunistic, though they can be more regular if groups return to the same places over time. An example of citizen science being carried out in the Arctic to monitor plastic litter pollution is the use of the *Marine Debris Tracker* app. This is a free phone application that has been created through a partnership with the US's NOAA Marine Debris Program and the Southeast Atlantic Marine Debris Initiative at the University of Georgia. The app geotags plastic debris and uploads the data to a centralized website for public use. Data have been collected in the Arctic in Canada, Norway, Finland, and the USA (Alaska).

There are further national projects and efforts directed specifically towards tourists visiting the Arctic, e.g., by cruise ships (e.g., Mallory et al. 2021; ARCTOUR project, https://www.akvaplan.niva.no/en/projects-networks/malinor/). These projects aim to involve tourists in marine litter sampling as part of research (crowdsourced science) while at the same time stimulating environmental awareness. These efforts are, however, not ethically straightforward since the increasing pressure of tourism in the Arctic is part of the pollution problem.

Focal regions and ecosystems with current data gaps

The data available on litter and microplastics in different environmental compartments are unevenly distributed across the Arctic (Fig. 1). The Pacific region of the Arctic has very little information on litter and microplastics beyond beach litter and plastic ingestion in seabirds (Fig. 1). The Russian Arctic is another region where there are limited data on plastic pollution, although several ongoing projects are aiming to explore and collect data on litter and microplastics (Grøsvik et al. 2018).

River systems have been identified as one of the key conduits of plastics from terrestrial environments to the world's oceans transporting millions of tons of plastic annually to marine ecosystems (Horton et al. 2017; Lebreton et al. 2017; Harris et al. 2021; Meijer et al. 2021). The basins of several large rivers span the Arctic and the subarctic regions, and thus could be a route for litter and microplastics from the south to more northern latitudes (PAME 2019; Frank et al. 2021; Meijer et al. 2021). In general, little information is available on litter and microplastics in freshwater systems of the Arctic and more research is needed to add to the understanding of freshwater sources, sinks, and circulation of litter and microplastics. Source and surveillance monitoring should include large riverine systems and their watersheds to track the transport and fate of litter and microplastics. Monitoring of these riverine systems should include sampling along the flow of the river, and specifically upstream and downstream major potential sources of litter and microplastics. To collect data relevant to modelling the riverine input of litter and microplastics to the Arctic marine environment, monitoring in

Table 5. Summary of the types of monitoring that can be addressed by litter and microplastics monitoring via the eleven environmental compartments assessed in the monitoring plan.

Compartment	Immediate trend monitoring	Initial baseline mapping and future trend monitoring	Source/Surveillance monitoring	Effect monitoring
Priority 1				
Shorelines	X		X	
Water	X		X	
Sediments	X		X	
Seabirds	X		X	X
Priority 2				
Air		X	X	
Invertebrates		X	X	X
Fish		X	X	X
Priority 3				
Snow/ice			X	
Seabed			X	
Terrestrial soils			X	
Mammals			X	X

water and sediments should include monitoring within the estuaries of large rivers.

Local pollution sources are poorly investigated in the Arctic, which makes it difficult to determine their relative contribution to plastic pollution in the Arctic (PAME 2019). However, considering the general lack of sewage treatment and poor waste handling in the Arctic (Gunnarsdóttir et al. 2013; Halsband and Herzke 2019; Granberg et al. 2020), these contributions are likely important and should be subject to source and surveillance monitoring in environments and biota surrounding, e.g., outlets and dumping sites.

Generally, litter and microplastics have been studied to a greater extent in the marine environment than in the atmospheric, freshwater, and terrestrial environments. The understanding of the transport, fate, and accumulation of litter and microplastics in these compartments of the Arctic, and of their potential effects on species in these areas is limited. Connecting the environmental compartments of the Arctic in an ecosystem-based monitoring approach would provide a better understanding of the transport of litter and microplastics to the Arctic and their fate within the Arctic, including levels, trends, and sources. This aspect is discussed in more detail in Provencher et al. (2022) in this Collection. In addition, the atmospheric environment as a transport pathway of microplastics to the Arctic is not well-studied (Hamilton et al. In press). An increasing number of studies have indicated its significance (Bergmann et al. 2019; Evangeliou et al. 2020), and atmospheric deposition has been recommended as a Priority 2 initiative. Atmospheric monitoring is also important with a view to developing transport models for microplastics.

Data reporting

One of the purposes of harmonizing monitoring guidelines, is to be able to compare observations over time and space. To produce comparable observational data, it is important to harmonize methodology and standardize data reporting. The use of harmonized terminology and setting of standards at the level of data detail, along with the measurement of uncertainty, are critical parts of this process. For the eleven environmental compartments considered here, a detailed discussion on metrics and terminology for reporting is considered in AMAP (2021*a*), including a list of mandatory pieces of information for each compartment.

Existing databases that could be considered for the reporting of litter and microplastic data include the EBAS database hosted by the Norwegian Institute for Air Research (NILU), the Environmental Database (DOME) of the International Council for the Exploration of the Sea (ICES), EMODNet used in the EU MSFD, OSPAR for shoreline and seabird data, the US's NOAA databases for shoreline data, and the Polar Data Catalogue (PDC). Databases already available for atmospheric pollution, like EBAS, can be modified to store and publish monitoring data, linked with other atmospheric data from the same site. ICES, NILU, NOAA, OSPAR, and PDC have developed standard procedures for the reporting of data to their databases and these should be followed. These procedures define the minimum mandatory information that must be reported but need to be adapted specifically for litter and microplastics for most environmental compartments. In addition, the procedures support the reporting of optional information, depending on the monitoring objectives. It is important to recognize that the various databases handle different data parameters, and some level of harmonization will be necessary across the databases on a global level to facilitate comparisons. Data treatment will impact the data generated in the future. Further discussions on data treatment and recommendations for data reporting are provided by Primpke et al. (2022) in this Collection.

Conclusion and next steps

Litter and microplastics monitoring and research questions in the Arctic are of high priority, as governments and organizations around the world aim to reduce plastic pollution in the environment. By examining what is known about litter and microplastics in eleven compartments we found that several different types of monitoring can be addressed in a comprehensive way through combinations of these environmental compartments (Table 5).

The proposed monitoring plan is envisioned as part of a series of phases of work on litter and microplastics to be carried out under the auspices of AMAP. The monitoring plan we propose here is based on best available knowledge at the time of writing, and the intention is to regularly update the technical guidance and the monitoring plan to provide up to date information for evidence-based decision-making. Next steps will focus on implementing the recommendations above where possible, and in context to what is relevant for a specific region of the Arctic. Future work will aim to build on this increased information from the coordinated monitoring efforts to better inform discussions on sources, transport, fate, and biological effects of litter and microplastics.

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