AMAP LITTER AND MICROPLASTICS

MONITORING GUIDELINES

ARCTIC MONITORING & ASSESSMENT PROGRAMME

version 1.0

AMAP
Arctic Monitoring and Assessment Programme (AMAP)

AMAP LITTER AND MICROPLASTICS

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Preface

Concerns about microplastics and litter in the environment have been raised at both global and regional (Arctic Council, EU, OSPAR, Nordic Council) levels. The *Working Group on Marine litter plastics and microplastics and its POPs and EDC*[1] *components: challenges and measures to tackle the issue* (Gallo et al., 2017) discussed the potential impacts of marine plastics on marine biodiversity and human health (November 2016).

The Nordic Council of Ministers' declaration (2017) on reducing the environmental impacts of plastics states that the Nordic countries aspire to be driving forces in efforts to promote a sustainable approach to the production, use, waste management, and recycling of plastics, and the council has decided to launch a program to follow up on this issue.

The *Fairbanks Declaration* from the Arctic Council (2017) notes "(…) growing concerns relating to the increasing levels of microplastics in the Arctic and potential effects on ecosystems and human health."

The Arctic Monitoring and Assessment Programme (AMAP) is mandated to:

- monitor and assess the status of the Arctic region with respect to pollution and climate change issues.
- document levels and trends, pathways and processes, and effects on ecosystems and humans, and propose actions to reduce associated threats for consideration by governments.
- produce sound science-based, policy-relevant assessments and public outreach products to inform policy and decision-making processes[2].

AMAP (2017) reported on environmental concentrations and trends of marine plastics and microplastics and about the biological and toxicological effects of microplastics (MP) in the Arctic.

The Arctic Council Working Group, Protection of the Arctic Marine Environment (PAME), conducted a desktop study on marine litter in the Arctic region (PAME, 2019). The report recommended developing a *Regional Action Plan on Marine Litter in the Arctic* (ML-RAP), and this plan was approved by the Arctic Council in 2021.

Despite the significant increase in available data on MP pollution and litter debris globally, including in the Arctic, status reports lack standardization in methodology and reporting consistency. For macroplastics, methodology exists in some regions (e.g., OSPAR). For MP, there are at present no harmonized measurements, monitoring methods, or environmental indicators. How the extreme environmental conditions of the Arctic might affect plastic transport and degradation processes is not yet known. Emerging knowledge from lower latitudes may not be transferable to the Arctic environment, so studies specific to Arctic conditions are needed.

The AMAP Litter and Microplastics Expert Group (LMEG) was established in the spring of 2019 with the mandate to:

[1] endocrine disrupting chemicals
[2] https://www.amap.no/about

1. Develop a monitoring plan and program for the monitoring of MP and litter in the Arctic environment. The program design should secure the necessary information that can quantify and document levels, trends, and impact/effects of MP and litter in the Arctic environment.
2. Develop necessary technical guidelines supporting the monitoring plan and program. The guidelines should include:
   - Harmonized sampling of the biotic and abiotic matrices in the Arctic environment;
   - Guidance on matrix and site selection;
   - Standardized sample processing and analytical methods;
   - Quality assurance/quality control (QA/QC) procedures;
   - Guidance on data management and data reporting;
   - To the extent possible, a proposed set of standardized methods that would lead to an assessment process.
3. Formulate recommendations on these topics and identify areas in which new research and development are necessary from an Arctic perspective.

These technical guidelines—the *AMAP Litter and Microplastics Monitoring Guidelines*—support the *AMAP Litter and Microplastics Monitoring Plan* (AMAP, 2021) and the *Regional Action Plan on Marine Litter in the Arctic* (PAME, 2021). The guidelines have been prepared by LMEG and its experts from Canada, Denmark, Faroe Islands, France, Germany, Iceland, Italy, Norway, Sweden, and the USA, and have been subjected to an independent, external review prior to publication.

This is version 1.0 of the document. It is expected that the document will be updated, and future versions will be under version control.

The views expressed in this document are the responsibility of the authors of the report and do not necessarily reflect the views of the AMAP Working Group, the Arctic Council, its members, or its Observers.

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Photo: Jakob Strand

Beach litter survey in Nuuk, Greenland.

1.0 Introduction

Plastic pollution in the environment is of increasing ecological concern worldwide (UNEP, 2014). As early as the 1970s, plastic litter in the marine environment was reported as a problem (Carpenter et al., 1972). Today, plastic pollution is observed across all oceans as well as in terrestrial and freshwater environments, even in remote regions such as the Arctic. Plastic pollution can enter the Arctic environment through local sources such as communities, landfills, shipping, tourism, and fisheries (PAME, 2019), but also from southern areas via transport by ocean currents, wind, sea ice, or biota (Cózar et al., 2014a; Obbard et al., 2014). Consequently, plastic pollution has been found across the Arctic environment, including on beaches (Bergmann et al., 2017; PAME, 2019), in snow (Bergmann et al., 2019), in surface, subsurface, and seafloor water samples (Bergmann and Klages, 2012; Cózar et al., 2014b; Huntington et al., 2020), and in sea ice (Obbard et al., 2014; Peeken et al., 2018). Recently, microplastics (MP) have been reported in amphipods (*Gammarus setosus*; Iannilli et al., 2019), snow crabs (*Chionoecetes opilio*; Sundet, 2014), and fish (Morgana et al., 2018), whereas the detection of plastics in Arctic seabirds dates back to the 1960s (Provencher et al., 2017; PAME, 2019; Baak et al., 2020).

Plastic pollution can have deleterious impacts on biota in a variety of ways, depending on consumer species and the shape, size, and type of plastic (de Sá et al., 2018), but most documented impacts are from entanglement and ingestion. Marine mammals, seabirds, turtles, and fish can become entangled in fishing gear, rope, and plastic bags (Laist, 1987; Gregory, 2009; Provencher et al., 2017). If not directly causing mortality, entanglement by and ingestion of plastic pollution may affect the fitness of individual organisms by compromising their ability to capture and digest food, reproduce, migrate, and/or escape from predators (Galloway et al., 2017; Rochman et al., 2019). As plastics break down in the environment, they become available to a broader range of organisms. Ingestion of MP has, in some cases, resulted in physical damage such as obstruction or internal abrasions (Wright and Kelly, 2017). In addition to physical effects, marine plastics can transfer chemicals to the marine environment, concentrate them from seawater, or act as vectors for alien species, such as bryozoans, barnacles, polychaete worms, hydroids, and molluscs (Barnes et al., 2009; Hermabessiere et al., 2017). Despite the significant increase in available data on MP pollution and litter debris globally, including in the Arctic, status reports lack standardization in methodology and reporting consistency. For macroplastics, methodology exists in some regions (e.g., OSPAR). For MP, there are at present no harmonized measurements, monitoring methods, or environmental indicators.

Although first reports on plastics in the Arctic date back several decades, the environmental fate of litter and MP is far from understood and is a field of ongoing research. How the extreme environmental conditions of the Arctic might affect plastic transport and degradation processes is not yet known. Emerging knowledge from lower latitudes may not be transferable to the Arctic environment, so studies specific to Arctic conditions are needed. The role of chemical sorption to or release from plastic particles is a subject of research interest, and of particularly great interest in the Arctic because of important subsistence harvesting in the region. Improved understanding of processes related to plastics in the Arctic will be highly relevant for modeling approaches as well as risk assessments and will likely further shape the design of monitoring activities in the Arctic.

1.1 Purpose of the guidelines

The purpose of the guidelines is to review existing knowledge and provide guidance for designing an Arctic monitoring program that will track litter and MP. The topics of litter, plastic pollution, and MP are addressed in many fora, including several of the Arctic Council working groups: Arctic Monitoring and Assessment Programme (AMAP; https://www.amap.no/documents/doc/amap-assessment-2016-chemicals-of-emerging-arctic-concern/1624), Protection of the Marine Environment (PAME, 2019), and Conservation of the Arctic Flora and Fauna (CAFF). The development of an Arctic monitoring program and its technical approaches will be based on the work that already exists in other programs such as those of OSPAR, the Helsinki Commission (HELCOM), the International Council for the Exploration of the Sea (ICES), the Organisation for Economic Co-operation and Development (OECD), and the United Nations Environment Programme (UNEP).

Plastic pollution is typically categorized into items and particles of macro-, micro-, and nano-sizes. These guidelines address macrosized litter as well as MP (< 5 mm), essentially including smaller size ranges (> 1 µm). However, determination of nanoplastic (< 1 µm) particles is still hampered by technical challenges, as addressed in Section 4.3 *Analytical methods*, and thus not currently considered in the current recommendations. Although most studies have addressed marine litter and MP, these guidelines also comprise the Arctic's terrestrial and freshwater environments.

Thus, the objectives of the guidelines are to:

1) support litter and MP baseline mapping in the Arctic across a wide range of environmental compartments to allow spatial and temporal comparisons in the coming years;
2) initiate monitoring to generate data to assess temporal and spatial trends;
3) recommend that Arctic countries develop and implement monitoring nationally via community-based programs and other mechanisms, in the context of a pan-Arctic program;
4) provide data that can be used with the *Marine Litter Regional Action Plan* (ML-RAP) to assess the effectiveness of mitigation strategies;
5) act as a catalyst for future work in the Arctic related to biological effects of plastics, including determining environmentally relevant concentrations and informing cumulative effects assessments;
6) identify areas in which research and development are needed from an Arctic perspective; and
7) provide recommendations for monitoring programs whose data will feed into future global assessments to track litter and MP in the environment.

To achieve these objectives, the guidelines present indicators (with limitations) of litter and MP pollution to be applied throughout the Arctic, and thus, form the basis for circumpolar comparability of approaches and data. In addition, the guidelines present technical details for sampling, sample treatment, and plastic determination, with harmonized and potentially standardized approaches. Furthermore, recommendations are given on sampling locations and sampling frequency based on best available science to provide a sound basis for spatial and temporal trend monitoring. As new data are gathered, and appropriate power analyses can be undertaken, a review of the sampling sizes, locations, and frequencies should be initiated.

Plastic pollution is a local problem in Arctic communities, and thus, guidelines and references need to include community-based monitoring projects to empower communities to establish plastics monitoring with comparable results across the Arctic. Community-based monitoring is an integrated part of the objectives of this report.

The monitoring program design and guidelines for its implementation are the necessary first steps for monitoring and assessment of litter and MP in the Arctic. The work under the AMAP LMEG is taking a phased approach under this new expert group. The first phase (which included the development of these Monitoring Guidelines) focuses on a monitoring framework and set of techniques for physical plastics. Later phases of the work will extend to assessments of levels, trends, and effects of litter and MP in the Arctic environment.

The guidelines strictly cover environmental monitoring of litter and MP. This does not include drinking water or indoor air quality tests. Additionally, although there is an emphasis on examining litter and MP in biota that are consumed by humans, and thus of interest to human-health questions, the guidelines do not consider MP ingestion by humans.

1.2 Existing frameworks with relevance for litter and microplastics monitoring

Legal frameworks applicable to marine plastic pollution are complex and consist of international, national, regional, and local policies, which cover ocean- and land-based sources of marine plastic. Several review documents exist for policies that directly or indirectly can be applied to mitigate the impact of marine plastic (Pettipas et al., 2016; Xanthos and Walker, 2017; PAME, 2019; Linnebjerg et al., 2021). The United Nations recommended that current international and regional frameworks on marine plastic pollution be reviewed to identify gaps for policy improvement (UN, 2017). Although MP in terrestrial ecosystems have been recognized as having a potential effect on biogeochemical processes (Rillig and Lehmann, 2020), no similar frameworks have yet been established for the terrestrial environment.

Preventing plastic pollution from entering the marine environment is a topic of priority across the globe, and there are a range of legally binding and non-binding international conventions that directly or indirectly address marine debris (e.g., Kershaw et al., 2013; PAME, 2019; Linnebjerg et al., 2021). One of the first global treaties to protect the marine environment from human activities was The London Convention that came into force in 1975. This convention was followed by The International Convention for the Prevention of Pollution from Ships (MARPOL), the United Nations Convention on the Law of the Sea (UNCLOS), and The Basel Convention. Together, all of these treaties have formed the foundation of international regulations to reduce this environmental pollutant.

The protection of specific marine environments through regional regulations plays an important role in the concretization of international regulatory frameworks. One of United Nations Environment Programme's (UNEP) initiatives is The Regional Seas Programme (launched in 1974), and, in cooperation with regional organizers, it has implemented activities related to the prevention and reduction of marine debris that have been consolidated by legal frameworks, e.g., the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). A list of international conventions, with relevance to the Arctic, which addresses the reduction of marine debris is presented in Linnebjerg et al., 2021.

Non-governmental organizations (NGOs) also play an important role in creating awareness about marine debris. One example is the International Coastal Cleanup from the US-based NGO, Ocean Conservancy, which removes marine debris from coastlines and collects data on the amount and types of marine debris removed (Ocean Conservancy, 2020). The Greenpeace *Call for a Plastic-Free Future* (Greenpeace, 2020) based on *Zero Waste Standards and Policies* (ZWIA, 2014) is another global initiative that aims to reduce plastic waste production and consumption. For example, in Russia, this initiative has resulted in many leading commercial networks considerably reducing the use of disposable plastic bags (Greenpeace, 2018).

For a thorough review of the policies that cover litter and MP in the Arctic see Linnebjerg et al., 2021. Briefly, among the Arctic countries, the Kingdom of Denmark (incl. Greenland and the Faroe Islands), Finland, Iceland, Norway, and Sweden have signed the OSPAR Convention. Denmark, Norway, and Iceland have implemented the OSPAR seabird monitoring component, however, Sweden has determined that monitoring fulmars is not feasible in Swedish waters. And, in Denmark and Norway, the OSPAR-based seabird monitoring takes place outside of the Arctic. Although other Arctic countries have applied the seabird protocol opportunistically (e.g., Canada; Poon et al., 2017), these studies are not part of a coordinated national policy or long-term monitoring program. Monitoring programs have also been initiated by the European Union, under the Marine Strategy Framework Directive (Galgani et al., 2013), by HELCOM, and in a number of national initiatives, for example, under the Northern Contaminants Program of Canada, as part of Canada's Plastics Science Agenda (ECCC, 2019).

Importantly, policies on plastic pollution vary widely across Arctic countries. Given that plastic pollution is subject to long-range transport, this inconsistency across the region is likely to reduce efficacy of actions for reducing plastic pollution and for monitoring changes over time. Therefore, for policies to be more effective, pan-Arctic coordination is required so that similar programs can be implemented in a harmonized and consistent manner. This cooperation needs to be facilitated at both the regional and international levels to ensure that litter and MP data from the Arctic are used in the context of global efforts to reduce litter and plastic pollution and minimize harm to the environment.

1.3 Importance of harmonization and standardization in litter and microplastics work

Efforts to map and categorize plastics in the Arctic have increased and coordinated monitoring under the auspices of AMAP is envisaged. Comparability of data in litter and MP is an ongoing challenge in plastic pollution research (Cowger et al., 2020; Provencher et al., 2020). Briefly, the term standardization refers to the application of specific methods according to robust criteria. These methods typically have limited flexibility to allow for comparability between laboratories. The benefit of this practice is that the community can understand how to compare the data to assess temporal and spatial trends. The limitation of this practice is that it significantly restricts the scientific freedom of method development. These standardized methods are commonly applied for standard analytical procedures, such as the International Organization for Standardization (ISO) and General Laboratory Practices (GLP) approaches.

Harmonization 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. Importantly, the limitations of each method are known, and the different activities/data generated can be combined. Comparison coefficients or scaling factors can be used when combing datasets.

There are examples in the litter and MP literature in which harmonization rather than standardization has led to studies from different regions being compared to assess spatial trends. For example, in the North Sea, the OSPAR Convention has developed a standard protocol for the collection and examination of Northern Fulmars *(Fulmarus glacialis)* to track trends in environmental plastic pollution (> 1 mm) in the region (van Franeker et al., 2011; van Franeker and Kühn, 2020). The North Sea protocol is based on beached birds being examined for ingested plastics. Since the early 2000s, the protocol has been applied to regions outside of the OSPAR, but often in regions where beached bird surveys are not possible (Provencher et al., 2017). In regions such as Arctic Canada, collections depend on local Inuit hunters to collect carcasses from local colonies or on fishers submitting fulmar incidentally caught in their nets. Although the collection methods are different, harmonization has been achieved and allows comparisons across and between larger regions. Researchers in the region have worked with international colleagues to ensure that methods are harmonized and thus can contribute to reporting standardized, comparable data across the northern hemisphere (Provencher et al., 2017).

Unfortunately, there are limited standardized methods for determining and assessing litter and MP in samples, although work is ongoing under ISO on standardized approaches for MP. Therefore, at this time, the litter and MP community is striving to harmonize methods in real time to compare levels and trends around the globe. We encourage the Arctic litter and MP community to engage in these global efforts to ensure comparability across studies. This includes global efforts to define methods, standard reference material, interlab comparisons, and suitable controls. Several efforts have focused on such harmonization, including those of the UN’s Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), and the Marine Strategy Framework Directive (MSFD) Technical Group for Marine Litter. Although the focus of these guidelines is the Arctic, it is important to recognize these global efforts so that any data collected in the Arctic on litter and MP are comparable globally and useful in larger litter and MP assessments. Thus, the following technical sections covering litter and MP methods in abiotic and biotic compartments are aiming for harmonized methods, which in some cases, may lead to standardized methods.

A monitoring program should provide concentrations of a target analyte in the medium, representative of the location and time of sampling. General issues to be considered are (1) definition of the target analyte in the case of plastic litter and MP, (2) detection limits (and other parameters describing data quality), and (3) detectability of temporal and spatial trends. Because national monitoring initiatives for plastic litter and MP should feed into circumpolar AMAP assessments, it is essential that they produce comparable data.

Plastics occur in a number of sizes, shapes, colors, and materials. As addressed above, the guidelines include all sizes of litter and plastics. Shapes include fibers, films, foams, beads, etc., also giving some indication of original products or materials. It is common practice to report a number of plastic particles or a mass of plastics per sample mass or volume, usually for a certain size range and/or for certain shapes.

This alone introduces variability in reporting, which makes comparisons between studies difficult. Weathering processes can have an impact on the number and characteristics of plastic particles. In addition, a plastic sample can include several types of synthetic polymers. This means standardization in terms of what is measured and reported is important, i.e., a definition of the target analytes.

Plastic materials are omnipresent in everyday use, and thus contamination of samples (and reporting of false positives) is a serious risk in all steps of sample handling. Any contamination and background levels also have direct impacts on the detection limits of the monitoring program. Therefore, standardized/harmonized measures must be taken to minimize this risk and to monitor potential contamination. Similarly, other parameters describing data quality, such as measurement uncertainty, will be affected by random contamination.

The importance of standardization and harmonization also applies to methods of sampling, storage and transport, sample processing, analytical determination, and quality assurance/quality control (QA/QC). In all steps, variability can be introduced. In general, knowledge of these sources of variability is still limited and will be explored further in the guidelines. The variability in the sampling and analysis has direct consequences for the detectability of temporal and spatial trends because large uncertainties will affect their statistical power.

1.4 Examining litter and microplastics across the Arctic

The following sections discuss litter and MP in 11 environmental compartments: air, ice/snow, terrestrial soils, aquatic and shoreline sediments, beaches, water, seabed litter, invertebrates, fish, seabirds, and mammals. These compartments span several Arctic ecosystems (e.g., tundra, lakes, rivers, coastlines, subtidal). Data from these compartments can be used to document the presence of a range of size classes of litter and MP in the environment and to improve the understanding of underlying processes.

For each of these environmental compartments, the following sections review the state of knowledge in the relevant compartment and identify a suite of primary and secondary monitoring indicators that have been described in relation to (1) the current state of methodologies (in each compartment) and (2) the feasibility for their use in monitoring initiatives across the Arctic. Primary monitoring indicators are those within each compartment that can be implemented immediately with current protocols and technologies to inform future litter and MP assessments in the Arctic. For example, examination of stomach contents in Northern Fulmars is the primary indicator identified in the seabird section for immediate implementation where possible.

Secondary monitoring indicators are those within each compartment that are viewed as needed for a holistic understanding of litter and MP in Arctic ecosystems but need further efforts to develop methodologies before being implemented at the pan-Arctic level. For example, in the seabird compartment, gut analysis of other species, as well as nest incorporation of litter are listed as secondary indicators that require more development before widespread implementation.

Some secondary monitoring indicators may also serve other specific monitoring purposes, for example, effect monitoring in relation to chemicals associated with plastic pollution that are of wide interest. The primary and secondary monitoring indicators are also thus linked to different types of monitoring with the main focus on baseline establishment, trend monitoring, and source/surveillance monitoring. Importantly, in each compartment, these primary and secondary monitoring indicators also address the actions outlined in the *Marine Litter Regional Action Plan* (ML-RAP).

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2.0 Guidance for Monitoring Abiotic Environmental Compartments

2.1 Wet and dry atmospheric deposition

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2.1.1 Introduction and description of purpose/aims of monitoring

Even with major research efforts happening on marine plastic pollution, the PAME report identified atmospheric circulation as a pathway to marine pollution still lacking in empirical data (PAME, 2019). Because there are only sporadic data available at this point and no harmonized methodology, no global estimate on the magnitude of atmospheric transport of microplastics (MP) to the Arctic is available. Nor will it be available in the near future. Additionally, local sources have not yet been investigated, thus the delocalization of macroplastic waste from landfills and urban settlements during storms is a possible route of transport within short distances (PAME, 2019).

Due to the still experimental nature of atmospheric sampling and the small number of peer-reviewed publications describing validated methods, no final recommendations on robust procedures are possible at this time. As an alternative, until validated methods are available, we are reporting on methodology by relevant publications and recommending best practices.

Like their marine counterparts, atmospheric MP consist of a variety of polymer types (Enyoh et al., 2019). Their morphologies show a similar variety of forms such as fragments, foams, films, granules, fibers, and microbeads (Enyoh et al., 2019), with fragments and fibers being the dominant MP (Dris et al., 2016, 2017; Cai et al., 2017; Zhou et al., 2017; Catarino et al., 2018; Allen et al., 2019; Ambrosini et al., 2019; Liu et al., 2019a, b). Allen et al. (2020) found that seaward winds had higher levels of MP associated with them than land-originating winds, suggesting that sea spray contributes to the atmospheric loads of MP.

Like marine MP, atmospheric MP may consist of up to 70% of additives and contaminants (Rummel et al., 2019). A recent report on nanoplastics in high altitude alpine snow indicates airborne transport of very small plastic particles that have unknown environmental and health impacts (Materić et al., 2020). Therefore, research on MP and especially microfiber transport in remote regions, like the Arctic, is utterly important in determining the dispersion of MP so that all aspects of their environmental impacts can be assessed.

Within the frame of atmospheric MP occurrence, three groups of MP distribution can be distinguished:

- i) wet deposition (mist, rain, and snow),
- ii) dry deposition (dust), and
- iii) suspended particles.

Microplastics in snow and ice on land are a direct result of atmospheric deposition combining wet and dry deposition (Ambrosini et al., 2019; Bergmann et al., 2019; Geilfusa et al., 2019); however, it is unknown if precipitation or snow deposits are a good proxy for deposition of airborne MP. In places like the Arctic, precipitation can vary substantially locally and is especially low in the desert-like conditions of the Canadian High Arctic. Precipitation is higher in the European Arctic.

Sea ice is not a good proxy for air pollution because sea ice will incorporate MP and microfibers from seawater into the ice. Microplastics in sea ice and snow on ice are discussed in Section 2.5, whereas land-based precipitation is covered in this section.

Compared to ocean currents, air currents can distribute atmospheric particles very quickly, within a matter of hours and days (Stohl, 2006). Like other atmospheric particles, MP are expected to undergo long-range transport in air currents followed by wet and dry deposition onto water and land (Allen et al., 2019) and will also undergo changes in the atmosphere, including hydrolysis, UV degradation, accumulation of organic films, and aggregation with other particles (Gewert et al., 2015).

Microplastics may also fragment into smaller pieces in the atmosphere, most likely increasing their long-range transport abilities (Biber et al., 2019). Microplastics vary in densities and shapes, causing, for example, microfibers to be more likely to travel longer distances than other MP because both the diameter and length matter for atmospheric transport (Allen et al., 2019; Zhang et al., 2020). In general, the atmospheric dry and wet deposition, or "fallout," as some plastics' publications erroneously refer to it, has not been well quantified as to its contributions to aquatic and terrestrial environments.

Local sources also exist in the Arctic, with short-range transport being relevant even with sparse populations. The contribution of local and long-range transport sources to MP in the Arctic are not quantified at this time.

2.1.2 Summary of available information/existing monitoring frameworks

The nature of atmospheric MP sampling and analyses is still in its infancy; thus, a number of locations have been investigated applying mostly experimental sampling methods. Reports from Europe (Dris et al., 2015, 2016, 2017; Catarino et al., 2018; Allen et al., 2019; Bergmann et al., 2019; Klein and Fischer, 2019; Vianello et al., 2019), China (Cai et al., 2017; Zhou et al., 2017; Liu et al., 2019a, b), Iran (Dehghani et al., 2017; Abbasi et al., 2019), and the Pacific Ocean (Liu et al., 2019b) have been published on airborne MP and reviewed by Zhang et al. 2020. The MP deposition, in the above studies, ranges from 1.5-221 MP/m^2/day. Of the conducted studies, atmospheric MP were found in a range of different compounds and morphologies akin to their marine counterparts. Abundance across studies varied considerably, and collectively they provided little information about size ranges and chemical composition.

The occurrence and distribution of suspended atmospheric MP (SAMPs) in the western Pacific Ocean provide field-based evidence that MP in the air can act as an important source of MP to the ocean (Liu et al., 2019b).

So far, there are no standard sampling and particle quantification/identification procedures for airborne MP. Further, reported sampling methods vary depending on indoor or outdoor sampling, as well as on whether measuring wet or dry deposition. A selection of reported sampling techniques is listed below:

Atmospheric microplastics

- Atmospheric deposition sample: passive air sampling using wet and/or dry deposition collector
    - Wet deposition sample: no data for wet deposition alone
    - Dry deposition sample: indoor air (Dris et al., 2016)

        - Dry/wet combined deposition sample: urban (Dris et al., 2015, 2016; Cai et al., 2017), alpine catchment (Allen et al., 2019)
    - Suspended air sample: active air samples using the pumps (low/middle or vacuum pump) equipped with particle filtering parts or mist sampler
        - indoor (Dris et al., 2017), urban outdoor (Kaya et al., 2018), suspended road dust (Abbasi et al., 2019), Northwest Pacific Ocean air (Liu et al., 2019), coastal air (Allen et al., 2020)
        - coastal mist using an active strand cloudwater collector (Allen et al., 2020)
    - Samples deposited on the surface: exclusive atmospheric-driven samples collected from the surface
        - deposited road dust (Abbasi et al., 2019), alpine and Arctic ice floe snow (Bergmann et al., 2019), alpine snow (Materić et al., 2020)

Monitoring airborne MP throughout the year in the Arctic is important to assess the impact of seasonal changes in wind patterns and the presence of UV light, as well as the impact of sea spray on atmospheric levels of MP and nanoplastics in both air and water (Allen et al., 2020).

Recommended particle size range for air sampling is 10-500 µm (although larger sizes should not be excluded) because the highest proportion of reported MP are < 500 µm (Enyoh et al., 2019; Zhang et al., 2019, 2020). For snow in European and Arctic regions, 98% of all MP were < 100 µm (Bergmann et al., 2019).

The lack of standardized active and passive sampling methods is hampering the comparability of studies, so no recommendations based on validated procedures and practices can be made at this time. However, strict quality assurance/quality control (QA/QC) procedures need to be followed to ensure reliable data, preferably carrying out sample treatment in a cleanroom or a laminar flow cabinet. To the extent possible, plastic-containing equipment should be avoided during field and lab activities (see subsection 2.1.6 for more details on QA/QC).

Chemicals transported by microplastics in air

As with MP found in the marine environment, both adsorbed pollutants as well as additives are part of atmospheric MP' chemical make-up. A broad range of analytical methods are available to determine the composition and concentrations of these chemicals (see earlier sections for more details). In general, adsorbed components (organic and inorganic, i.e., metals) are present at much lower concentrations compared to the additives, thus requiring ultra-trace analytical methods, whereas additive determination relies on the availability of a multitude of analytical techniques and instrumentations.

2.1.3 Trends in literature in Arctic regions

Atmospheric microplastics

So far, no atmospheric field studies have been conducted in the Arctic. The most recent examples for wet deposition are studies that reported MP in Arctic snow (Bergmann et al., 2019) and in alpine snow (Allen et al., 2019; Ambrosini et al., 2019; Materić et al., 2020). A recent modeling study (Evangeliou et al., 2020) globally simulated atmospheric transport of MP particles produced by road traffic (TWPs, i.e., tire wear particles and BWP, i.e., brake wear particles). The authors found high transport efficiencies of these particles to remote regions, suggesting that the Arctic is a particularly sensitive receptor region because of the light-absorbing properties of TWPs and BWPs, which cause accelerated warming and melting of the cryosphere (Albedo effect; Evangeliou et al., 2020).

Chemicals transported by microplastics in air

Microplastics, volatile siloxanes, and organophosphate esters share the same hotspot regions in the Canadian Arctic, indicating similar sources, possibly undergoing the same transport processes caused by their shared origin from plastics (Panagopoulos Abrahamsson et al., 2020; Sühring et al., 2020; Adams et al., 2021).

2.1.4 Benefits and limitations

Benefits

Conducting research in the Arctic for atmospheric MP is crucial for the evaluation of their distribution, sources and fate, contribution of local and remote sources, and how they will affect the Arctic. Further, we need to understand how atmospheric MP are contributing to marine MP loads because of their differing types, sizes, and chemical loads due to their different emission sources, transformation processes, and fate history.

Further, the improved understanding of local and long-range transport sources will assist in the formulation of legislation and remediation measures. Microplastic concentrations in indoor air are both important for the estimation of human exposure as well as for elucidating sources to MP in outdoor air. This is especially important for people living in the Arctic, who, due to harsh environmental conditions, stay indoors for long periods of time and have very well insulated homes with little air exchange.

The determination of chemicals added and sorbed to atmospheric MP would improve the knowledge base on their role as a vector for chemicals into the Arctic environment.

As climate change impacts the Arctic, melting ice and changes in atmospheric circulation patterns, primary and secondary emissions of MP, and, especially relevant to air, microfibers need to be investigated to determine the current transportation trends to, within, and out of the Arctic so changes and impacts can be estimated. Also, more extreme weather conditions will cause more physical damage to MP, as well as mixing between water and airmasses, further adding to the MP load in the atmosphere.

Limitations

Aside from the unavailability of a consensus on the applied methodology, the monitoring of atmospheric MP in the Arctic is highly limited by the remoteness of sampling locations and the challenges of the infrastructure. This is especially true for Arctic regions in Russia and North America, where the population is sparse and travel to and within is limited, difficult, and expensive. It is important to sample year-round to assess the seasonal changes in atmospheric circulation and transport of MP to the Arctic from different regions of the world. A representative sample size as well as the number of required replicates is a prerequisite for a valid method to collect a sufficient amount and a sufficient number of subsamples to adequately represent the sampled location.

Another limitation is the unavailability of highly trained and skilled operators, which are needed to effectively collect samples to reduce the risk of contamination and ensure a rigorous sampling regime.

Although all sampling, analyses, and polymer determination are very time consuming, requiring trained personnel and expensive instrumentation, the very small size of atmospheric MP make it even more prone to contamination during processing and analysis, thus requiring lab facilities with particle-controlled environments as a prerequisite for atmospheric sample analyses.

Other specific limitations include access to electricity for active air, and wet and dry only deposition sampling because the quantitative nature of active air sampling results in more reliable data than passive sampling in a shorter time frame. Limitations can be overcome by co-deploying active air, wet only, and bulk samplers at a few stations to assess their comparability. For example, in Canada, the Alert monitoring station, and in Svalbard, the Zeppelin station would be good candidates to assess this.

Wet only and bulk deposition sampling limitations in the Arctic include strong winds, e.g., blowing the particles out of the sampler, and the varying amounts of snow fall across the Arctic, e.g., some regions with large amounts of snow may bury the sampler whereas in other regions, desert-like conditions exist with very little snowfall in a season.

For all types of samplers left in the field, there is the potential for wind, snow, and animal damage to the equipment. Due to extreme weather conditions in the Arctic, the lack of consistent access to sampling equipment may also be a limitation.

2.1.5 Sampling strategy and methodology

Sampling strategy: There are limited options to collect air samples in the Arctic for MP because of the remoteness of sites, harsh conditions, and limited access to power. Typical sampling includes active air samplers, bulk deposition samplers, and wet deposition samplers. Active air samples will provide a quantitative number of particles per meter cube of air; however, active air samplers for air monitoring networks are expensive, require power, require an operator to change filters, and give data over a very short time snapshot of the air. Passive samplers, advantageously, can be installed at existing atmospheric monitoring sites in the Arctic, reducing the need for manpower and infrastructure. Bulk deposition samples give a total of wet and dry deposition without the need for power, can be integrated over a longer period of time (e.g., typically one week or one month); whereas, wet only and dry only samples give more detailed information but require power and a specialized sampler. To their disadvantage, bulk deposition and dry deposition samples overestimate the size of atmospheric particles because larger particles settle out more quickly, and smaller fibers stay suspended in the air for a longer time. If smaller particles do settle out, they may become re-suspended in the air more easily than larger particles (Rezaei et al., 2019). Wet deposition samples probably provide a better representation of the atmospheric load of MP because precipitation washes the air column of particles, however in all cases of bulk deposition analyses, a quantitative evaluation of airborne particles is challenging. Outdoor passive air samplers are being developed and tested but results have yet to be released.

For both alternatives, the co-location at existing monitoring sites is highly beneficial because it enables the simultaneous delivery of supplemental data on other atmospheric measurements, also enabling back-trajectory analysis of possible sources, event-analyses, and input in databases and modeling actions. These types of sampling networks are sparingly distributed in the Arctic, but at key locations.

Independent of the sampling method chosen, sampling for atmospheric MP should be continuous throughout the year, covering shorter periods of time, to give insights into seasonal changes of wind patterns and any short-term transport events.

Replicates: It is difficult to collect replicate active air, wet only, and dry only samples because of the power and duplicate samplers' requirements but replicate bulk deposition samples are encouraged. Nipher gauges are a well-established method of collecting snowfall in higher wind environments. A type of bulk air deposition sampler that buffers the wind and limits resuspension of particles from the sample is encouraged.

Not recommended:

1) Air sampling, including deposition sampling, from ship-board platforms is not recommended. Ships are a source of contamination to the surrounding air because they vent substantial amounts of air from their systems including engine, HVAC, and laundering exhausts, which contain MP that would contaminate air samples. However, a wind-sectoring system can collect the air inflowing from the head of the ship and can exclude the collection of air inflowing from the other sides of the ship. This system can be used to prevent ship-based contamination.
2) Grab snow sampling, especially one-time opportunistic sampling, is not recommended. Snow sampling gives a snapshot of the MP in snow, but it is impossible to determine the age and history of the snow if no additional parameters are measured, or if fresh snowfall is collected. As an alternative, bulk deposition samplers are recommended. Ice/snow cores from overland are encouraged especially if paired with other chemical analyses that provide ancillary data when interpreting the MP data. Ice cores from over water are discussed in Section 2.2.
3) Opportunistic sampling is not recommended except when rigorous QA/QC are maintained.
4) Subsampling is not recommended because MP are not homogenously distributed within the sample.

Sample treatment

It is recommended to process the samples as little as possible to avoid contamination, together with storing the samples in plastic-free, precleaned containers. Digestion steps can fragment the particles and fibers, biasing the number and size distribution of the MP, and are generally not needed for atmospheric-related sampling, although there are exceptions.

More processing steps expose the samples to more sources of contamination, which are critical to avoid because of the small particle sizes in air. As with other MP sampling, all water used for rinsing must be HPLC grade or Milli-Q water and DIW that have undergone additional filtration using the same filter types as with sampling to remove plastics from the water filtering system. Specific to bulk, dry, and wet deposition, sample collectors must be rinsed thoroughly to remove MP from the walls of the sampler and subsequently filtered with filters applicable to the research question and measuring technique (pore size, diameter, material). For active air samples, direct transfer of the filter to the analytical instrumentation with no processing is recommended. If not possible, due to high particle loads, e.g., no monolayers can be ensured, particles need to be re-suspended by ultrasonification in water, subsampled, if necessary for higher load samples and filtered. Although ultrasonification may cause particles to fragment, so it should be minimized.

Sample analyses

It is imperative that particle specification methods are included, for example, polymer type, shape, length, and diameter. Sample analyses should include microscopy and fluorescence microscopy, if using Nile Red, paired with Raman spectroscopy and/or µFTIR to screen suspected MP. As an inexpensive, fast screening method, staining with lipophilic Nile Red can be chosen for identification of larger MP > 20 µm (for rapid screening under a fluorescence microscope; Maes et al., 2017). That being said, Nile Red cannot determine polymer type and disagreement within the MP community about the usefulness of Nile Red treatment does exist.

Samples should only be subsampled when there are substantial particle loads, preventing a monolayer of particles on the filter, disabling the identification of the particle composition. No homogeneity of particle distribution can be assumed in the sampler and/or filter. Also, high particle load is not typical in atmospheric related samples in remote Arctic regions.

Because the availability of analytical methodology for particles < 20 µm is limited, it is important to subset and archive samples when possible in a contamination-free, dark, and cool environment (< 15 ºC). However, the low levels of atmospheric MP in the Arctic may limit subsampling and the limited access to samples may limit the ability to sample archive.

2.1.6 Quality assurance/quality control (QA/QC) and reporting/data management

Here we discuss QA/QC as it pertains to atmospheric related sampling (see also Brander et al., 2020 for a wider discussion of MP QA/QC protocols).

Harmonized terminology: To mitigate inconsistent terminology and to enable translation of the data to atmospheric particle research in general, terminology defined in atmospheric science should be used.

Sampling: Opportunistic sampling should be avoided except for research purposes, and to ensure a wide data comparability, systemic sampling and handling should be maintained. Replicated samples are highly recommended and should be considered when possible. Clothing worn during sample media preparation, collection, and recovery must be documented.

Contamination: The sizes of particles in air are, in general, smaller than other matrices, therefore, it is very important to follow stringent QA/QC procedures. Field, travel, and laboratory blanks are crucial steps to track and eliminate contamination. For field blanks (the sample collection containers are opened during sample collection), it is recommended that a representative number of field blanks and procedural blanks are taken (one blank per field sample or per sampling period). For travel blanks (sample collection containers are not opened in the field), it is recommended to take 1 blank per 10 samples. For laboratory blanks, three lab processing blanks per processing day should also be done. These blanks form the basis for the limit of detection, method detection limit, and limit of quantification so an evaluation can be made to ensure reported values in samples are statistically greater than the blanks. These values must be defined by the group reporting the data.

Strict routines for choice and preparation of sampling equipment (plastic free, fired at 450 ºC for > 4 hours) need to be followed, and the handling of samples under particle-controlled conditions (laminar flow fume hood with filtered air/clean room) is essential. A consensus needs to be developed on how field blanks are included and how blank subtractions are performed.

Recoveries: Spike recovery tests are highly recommended and are performed by adding a known number of particles (of several sizes) to blank filters and these are then processed as actual samples. These samples can also be used as blanks for other particles not intentionally added. As standard reference materials are developed, it is recommended that laboratories assess method efficiency by using them. Participation in intercalibration studies or round robin exercises is also strongly encouraged.

Reporting: Standardized methods for instrumental analysis and reporting (number, weight, size, length, and diameter) need to be developed. When reporting data, especially on microfibers, the length but also the diameter is important because both these dimensions have impacts on the transport, fate, and inhalation rate. Using more than one analytical technique to assess the presence and identity of plastic particles is important because microscopy, Nile Red, Raman spectroscopy, and FTIR methods used on their own, yield different types of information. Using these methods simultaneously can yield better interpretation of results but will increase the time spent on each sample dramatically. As sample scanning instrumentation becomes more widely available and used, the sample processing time will decrease. In general, facing a particle size range of nm to µm, dedicated requirements for the inclusion of MP data into existing databases for atmospheric pollution should be considered. The advantages of combining atmospheric MP data with already collected data on many other atmospheric pollutants and descriptors are considerable (e.g., EMEP, EBAS). This also includes the translation of particle abundance, reported in particle counts, into weights.

2.1.7 Existing monitoring for populations/contaminants in the Arctic

Currently, there are no standardized and/or harmonized monitoring methods for air available with only very limited reports of atmospheric MP, and no reports in the Arctic. Current active air sampling, passive sampling, bulk deposition, wet deposition, and dry deposition methodology need to be adapted to Arctic conditions and requirements for robust and reliable data.

2.1.8 Suggestion for future activities/knowledge gaps

The area of atmospheric MP is still in its infancy with many data gaps and a less than robust database, hampering any conclusions on the role of the atmosphere in Arctic MP pollution.

However, experiences and lessons learned from the well-developed research on marine MP can be used and adapted especially with respect to sample handling, QA/QC, quantification, and identification of MP.

The recent report published by PAME, 2019 identified the following gap: “Atmospheric Transport - There is a big research gap with no current studies being able to quantify plastics from long-range winds, and other air-based vectors.” Although this report also recommends sampling ice floes to improve estimates of atmospheric transport of litter, we do not recommend this because ice floes have atmospheric sources but also incorporate plastics from water and sea spray (Allen et al., 2020), so assuming the MP in ice floes are only from atmospheric deposition would lead to an overestimate of atmospheric deposition.

Field measurements of known emission sources have yet to be undertaken. Primary and secondary emissions redistribute MP back into the air from seawater as waves break (Allen et al., 2020) and/or they may be suspended from terrestrial surfaces by wind (Rezaei et al., 2019). Melting sea ice and glaciers can also lead to a redistribution of atmospheric MP. Studying the depositional fluxes at the air-water interface is essential for investigating MP behavior in dynamic systems (Galgani and Loiselle, 2019) and to estimate the loadings of atmospheric-related particles to land and sea surfaces. Particles undergo deposition onto water and land surfaces, however, the behavior and fate of MP on water surfaces will differ from deposition on land.

Trajectory models should be applied to determine the trends of long-range transport vs. local transport and to evaluate event-based transport. Trajectory models and other atmospheric transport models could lead to insights on the emission sources of airborne MP. Field measurements need to be carried out complementarily, to both validate the transport models and to identify relevant sampling locations and periods, saving time and effort. This work needs to be coupled with experimental determination of aerodynamic features of MP and microfibers to feed correct variables into the model describing their atmospheric transport using existing global distribution models.

The presence of other anthropogenic microfibers, e.g., cellulose fibers that are associated with anthropogenic dyes and/or chemicals in atmospheric-related samples, is also worth documenting when undertaking MP analysis. Cellulose fibers such as cotton, rayon, linen, and hemp are highly processed and contain up to 30% added chemicals, which may enhance their persistency in the environment; e.g., cellulose fibers from blue jeans are found in deep Arctic ocean sediments (Athey et al., 2020).

Table 2.1 Monitoring and research recommendations divided into must do and should do.

	1st level (must do)	2nd level (should do)
Monitoring	• Bulk deposition (wherever possible, duplicates wherever possible), one week integrated sample • Wet deposition at one-two locations per region, where existing stations and power source are available; one week integrated sample • Active air sampling at one-two locations per region where existing stations and power source are available, > 2500 m^3 Must have data: • Location • Date • Collection method • Polymer type • Particle number/weight, length, diameter, shape, color • Subsampling and archiving of samples when possible Context • < 500 µm although larger particles will also be counted • Active air: particles/m^3 • Bulk deposition: particles/day/m^2 • wet deposition: particles/L • when using pyr-GC/MS or other destructive methods for small particle size ranges (< 20 µm), weight-based reporting is encouraged (µg/ L/ m^2/ m^3) • Locations: see map	• Dry only deposition Must have data: • Location • Date • Collection method • Polymer type • Particle length, diameter, shape, color Context • < 500 µm although larger particles will also be counted • Dry deposition: particles/day/m^2
Research	• Relate to other classes • Best filters to be used for active air sampling • Sampling amounts and periods • Sampler design • Cross-contamination issues • Determination of MP composition • Methods for measuring chemical compounds related to MP (additives) • Suitable instrumentation • Relate to additional atmospheric data	

Table 2.2 Summary rationale for recommendations, including estimated costs for implementing programs; 0 - litter and plastic pollution monitoring already in place with regular funding; $ - relatively inexpensive because new litter and microplastic monitoring programs can use existing programs to obtain samples in at least some regions, but need to have some additional capacity to process samples for litter and plastic pollution; $$ - either sampling networks and/or capacity need to be developed to monitor litter and microplastic pollution; $$$ - development of sampling networks, processing capacity of samples, and reporting all need to be developed in the majority of the Arctic regions.

Recommendation	Program Cost	Rationale
Primary Recommendations		
Bulk deposition (wherever possible, duplicates wherever possible).	$	This sampling type can be easily set up at existing sampling sites or in northern communities. It may involve some money to purchase supplies, shipping, and training the operator.
Wet deposition at one-two locations per region, where existing stations and power source are available.	$$	Existing research programs are already in place at sites throughout the European and Canadian Arctic but there are still substantial costs associated with this type of sampling: the shipment of equipment to remote locations, installation of the sampler, a required power source, and an operator.
Active air sampling at one-two locations per region where existing stations and power source are available.	$$	Existing research programs are already in place at sites throughout the European and Canadian Arctic but there are still substantial costs associated with this type of sampling: the shipment of equipment to remote locations, installation of the sampler, a required power source, and a skilled operator to calibrate the pump and change the filters.
Secondary Recommendations		
Dry only deposition.	$$	Existing research programs are already in place at sites throughout the European and Canadian Arctic, less so in Russia but there are still substantial costs associated with this type of sampling: the shipment of equipment to remote locations, installation of the sampler, a required power source, and an operator.

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2.2 Water

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2.2.1 Introduction

The first assessments of plastic in the global oceans were based upon items floating on the ocean surface or immediately below. The ocean surface accounts for most studies conducted on plastic pollution to date. This is likely in part because roughly half of all plastic produced is less dense than seawater and expected to float at sea (Geyer et al., 2017) and partly because water is one of the easiest and cheapest domains to study. We are now fully aware that plastics of various sizes are everywhere, and all water bodies, either freshwater or marine, can be sampled to study the presence of plastics from surface waters or within the water column.

The broad distribution of plastics is assumed to be related to their longevity in the environment; they degrade very slowly, mainly through mechanical abrasion and exposure to UV radiation. Water surfaces and the upper water column (especially in the sea) are very dynamic and provide a connection between coastal, inland waters, and offshore areas facilitated by water movement and transport patterns and processes. The relatively high buoyancy of many plastics facilitates transport from source areas, which may involve long-distance or even global-scale transport. Floating plastics can also be transported vertically. Many processes are involved in vertical displacement including density, buoyancy, size, degradation, biofouling, and other biological interactions. As a result, we are now aware that plastics move between water compartments because of their physical, mechanical, and biological properties (Choy et al., 2019; van Sebille et al., 2020).

The inclusion of plastics in water monitoring programs must consider this complex scenario and focus on useful and affordable actions to collect time series, which are the primary tool to verify whether remediation actions are effective.

Sampling strategies for monitoring must relate to the specific goals of the monitoring program. For example, does one want to investigate accumulation areas, input related to point sources (e.g., effluents from wastewater treatment plants or industries), input from freshwater water ways (rivers, creeks, etc.), or long-range transport? The sampling methods available for each program may be different depending on which compartment and which size of plastic is being monitored. Further, the selection of sampling location may be constrained by the facilities and infrastructure available to specific nations. Other important aspects that might need to be considered are the inherent properties of the chosen environment as well as the sampling season. For example, surface sampling nets are impractical in open waters when there is high biomass, adverse weather conditions, and sea ice.

Critical analysis of methods and many general considerations about monitoring have been highlighted by many working groups at a global scale, some of them are reported in subsection 2.2.3, but they were not specific to the Arctic. We therefore focus on the specific issues that are relevant for the Arctic to implement global, general-use recommendations for local application.

2.2.2 Status of global science

In polar regions, records of plastic pollution in the Arctic date back to the 1960s, with some observations of plastic debris and relative consequences for marine life from Alaska (Threlfall, 1968). Large floating plastic items have been observed at sea dating back to the 1970s, and included plastic bottles, ropes, balloons, and rubber shoes (Venrick et al., 1973). Similarly, researchers began sampling small plastics from oceanic surface waters around the same time (Carpenter and Smith, 1972). Long-term data sets have emerged from the Pacific (Law et al., 2014) and Atlantic (Law et al., 2010), as have numerous global ocean models (Mountford and Morales Maqueda, 2019; van Sebille et al., 2020). Freshwater water bodies are comparatively less studied (Mendoza and Balcer, 2019).

In terms of the Arctic, large plastic items are routinely reported floating in the surface waters of the Barents Sea and Fram Strait (Bergmann et al., 2016; Grøsvik et al., 2018). Norway and Russia have a long-term collaboration of monitoring fish resources in the Barents Sea used for determining fisheries quotas, and from 2004, this monitoring was extended to include ecosystem-based monitoring. From 2010, the monitoring also included recording floating marine debris and litter as bycatch in trawls. The ecosystem survey in the Barents Sea covers a station net of approximately 300 stations and is performed between August-October each year (Eriksen et al., 2017). Similarly, in the Canadian Arctic, at-sea surveys of seabirds have been expanded to include floating marine debris (Mallory et al., 2021).

Specific investigations targeting microplastics (MP) in the Arctic began by using vessels of opportunity to collect data from offshore seawater (Lusher et al., 2015; Kanhai et al., 2018, 2020), as well as surface sampling using, e.g., manta nets (Cózar et al., 2017). There are historical records of small plastic items captured in surface sampling nets dating back to the 1970/1980s in the Bering Sea and the Gulf of Alaska (e.g., Shaw, 1977; Day and Shaw, 1987; Day et al., 1990). Research vessels often have an underway seawater pump, positioned in the subsurface waters to collect information such as temperature, salinity, and conductivity. Lusher et al., 2015 used this to collect back-to-back samples while a research vessel was on a transect from northern Norway (Tromsø, 69.65° N, 18.95° E) to the south west of Svalbard (78.1° N, 18.8° W). They also collected manta net samples (> 330 µm) along the same route intermittently. The average number of particles collected using the pump was 2.68 ± 2.95 particles per m^3 (range 0.00-11.5 particles per m^3), whereas the manta net results yielded lower values, 0.34 ± 0.31 particles per m^3 (range 0.00-1.31 particles per m^3). Similarly, Cózar et al. (2017) demonstrated how manta nets could be used to collect information on plastics floating in the surface waters during a circumpolar expedition. Out of the 42 samples collected, plastic debris (> 500 µm) were generally scarce, however the investigation did point to higher concentrations in the Barents Sea and Greenland areas compared to the other regions of the Arctic. Additional manta net investigations have been carried out in the Bering Sea (0.091 ± 0.094 particles per m^3), Northern Pacific (0.030 ± 0.017 particles per m^3), and Chukchi Sea (0.23 ± 0.07 particles per m^3; Mu et al., 2019). To date, the most northerly manta net sample has been carried out close to the edge of the North Pole ice shelf at 82°07' N (Aliani et al., 2020).

Nets are selective for some size classes of MP and miss relevant parts of the mass of floating megaplastic size class. They also fail to sample many particles smaller than the lower mesh size, which typically is dominated by smaller MP fragments and microfibers. This is evidenced by a recent study carried out in Nuup Kangerlua, a fjord in West Greenland (Rist et al., 2020). Pump sampling (5 metre depth, 10 µm lower limit) and bongo nets (surface, 300 µm lower limit) produced values with two orders of magnitude difference. Therefore, integration with pump and bucket sampling is envisaged to cover as many size classes as possible (Ryan et al., 2019) and is becoming more and more common in oceanographic expeditions.

Pump sampling was also used by Morgana et al., 2018 and Jiang et al., 2020 who reported values similar to those found by Lusher et al., 2015, confirming the ubiquitous presence of MP in the

Greenland Sea. Higher levels of MP were reported in surface waters underlying ice floes, 0-18 particles per m^3 (Kanhai et al., 2020). On the contrary, during an investigation of different water masses in the Arctic Basin, Kanhai et al. (2018), reported a lower average value, 0.7 particles per m^3 (range 0-7.5 particles per m^3). Water samples (218-561 litres) have also been taken in the water column of HAUSGARTEN (near surface, ~300 m, ~1000 m, and above the seafloor) with reported values ranging from 0-1,287 particles per m^3 (Tekman et al., 2020). The highest reported values were seen in subsurface waters. Although in many cases, subsamples were processed for data analysis (5-100%). Some of the highest values of MP have been reported in coastal water bodies near Ny-Ålesund, Svalbard (61.2 particles per m^3; Granberg et al., 2019).

Surface waters in the eastern Canadian Arctic waters of Nunavut were investigated for MP using bucket samples, reporting an average concentration of 0.22 ± 0.23 particles per L (Huntington et al., 2020). The concentrations were not related to the human populations suggesting that MP contamination in the Canadian Arctic is primarily driven by long-range transport.

Although scarce, data collected throughout the water column can be used to provide an insight into the three-dimensional distribution of MP in the Arctic (Amélineau et al., 2016; Kanhai et al., 2018; Tekman et al., 2020; von Friesen et al., 2020). Data collected in offshore waters and within the water column of the Arctic support the hypothesis that the water column constitutes a major reservoir for MP in the Arctic (Cózar et al., 2017). During an investigation of two oceanographically different fjords, Kongsfjord and Rijpfjorden, von Friesen et al., 2020 observed variable microliter concentrations along the two bathymetric gradients. Highest concentrations were identified in the subsurface samples from Kongsfjord (48 particles per L).

Studies of MP concentrations (> 100 µm, volume of 1-3 m^3) in the water column in Monterey Bay, California demonstrated the highest levels in water samples collected from depths just below the mixed layer (15 particles per m^3 at 200 m), at a deep site located 25 km from the nearest land. Microplastics concentrations near the sea surface (5 m) were among the lowest measured (median 2.9 particles per L) and were roughly equivalent to those of the deepest waters sampled (1000 m, median 2.9 particles per L). Concentrations were highest at intermediate depths into the mesopelagic zone (Choy et al., 2019). It must be noted that the density of polymers along with biotic and abiotic factors can alter a particle's buoyancy and this will influence the position location of plastics within the water column. There is evidence of items made of low-density polymers in the deep sea as well as high-density polymers floating on the ocean surface. In general, density is not a relevant property to explain vertical position or displacement of plastic. This is especially true for macrodebris. The presence of air bubbles or of certain shapes do not allow sinking. Polymer density may be relevant for MP or nanoplastics, but at these scales turbulence and surface tension may also be important.

Sources of plastics to the Arctic may include long-range transport from distant sources, or input from local sources such as urban centres (Rist et al., 2020), fishing, wastewater treatment facilities (Granberg et al., 2019; von Friesen et al., 2020), and melting of sea ice (i.e., released during; von Friesen et al., 2020).

At the time of writing, there has only been a single investigation of a small freshwater lake. Sediments adhered to rocks from a shallow lake (0.75m) near Ny-Ålesund and were investigated for anthropogenic particles. Microplastics were estimated to equate to 90 particles per m^2 (González-Pleiter et al., 2020).

No other investigations of freshwater bodies or rivers in the Arctic have been published. Although they are of interest due to the high volumes of riverine discharge into the Arctic regions from Russian and Canadian rivers.

2.2.3 Trends to date

Unfortunately, the investigations to date in the Arctic are difficult to compare because they use different methods, different reporting criteria, and different measurement values. Thus, there is currently no available data on the scientific trends.

Monitoring ideally should focus on identifying trends in sources to ensure that mitigation strategies and remediation efforts can be introduced close to source or accumulation areas, respectively. For trends to be monitored effectively in the Arctic, the differences between summer and winter seasons need to be considered as does the repeatability of sampling. For example, sampling in the Arctic can be costly and needs to be planned carefully (especially those efforts that require research vessels). Further, the winter season enforces its own limitations, ice-covered water cannot be sampled to produce informative or representative data. Without careful consideration, this may lead to gaps in information. The methods used should be harmonized throughout the AMAP regions.

Table 2.3 Summary of available data in the Arctic.

	Freshwater	**Marine**
Sources	Limited data	Limited data
Inshore	Limited data	Limited data
Offshore	-	Data available

2.2.4 Benefits of using water samples

In terms of macroplastics, visual observations of floating macroplastics can be conducted in parallel to bird and mammal surveys at no extra cost. Data gathered can help provide information on sources and potential interactions with biota. Microplastic sampling can be conducted using surface sampling nets or pumps, which are already used and recommended around the world, thus enabling the development of comparable datasets. Pump sampling can be conducted through seawater intakes on research vessels where a large amount of metadata is usually collected for characterizing the water column, allowing metadata to be directly compared to sampled MP. This can be important when sampling in areas where water stratification changes. Furthermore, many research vessels are already involved in long-term dataset collections, such as nutrients, therefore MP could be added to these routine sampling regimes using pump methods or towing a Ferrybox so as not to disrupt ongoing programs. The water column can be monitored to infer the vertical distribution of plastics. However, differentiating between those sinking or returning to the ocean surface is not possible at present.

Limitations of water sampling

Meteorological conditions are often a limiting factor for water sampling or monitoring efforts. Surface water monitoring is reliant on calm weather conditions. Visual surveys require good visibility. Surface sampling nets require stable surface conditions and can be severely hampered by large plankton blooms. Microplastic sampling using nets can also introduce sources of error from self-contamination, including sampler's clothing (microfibers) and sampling platform (i.e., but also from the research vessel, small boat, or other). All sampling of offshore waters requires access to research vessels, whereas coastal water and inland water sampling can probably rely on smaller, more easily accessible sampling platforms, although then, the equipment used needs to be similar. Coastal sampling can be hampered by changes in tidal directions.

2.2.5 Methods

Sample collection

Surface waters:

Surface water samples can be collected using different gear including nets and pumps to investigate MP. Several standards and recommended protocols have recently emerged for sampling MP. Table 2.4 summarizes the recommended protocols for each sample type. For example, a manta net can be deployed from a research vessel for a period of 10-30 minutes, with a speed of between 1 to 3 knots. After each tow, nets must be washed and rinsed onboard with properly filtered water from the outside using the deck hose, and the cod-end sampler should be removed and rinsed in contamination-controlled conditions. Samples are washed using filtered seawater and a series of clean metal sieves (e.g., 5 mm and 200 µm) to fractionate samples before subsequent analysis. Manta nets have limited use in rough seas; waves affect manta results and differences between GPS and flow meter data can occur as has been seen in the Arctic (Lusher et al., 2015) and through dedicated comparative studies (Michida et al., 2019). Wind speed may also affect the vertical displacement of particles in the upper layers of the water column (Kukulka et al., 2012) and wind stress and particle concentration were negatively correlated, with high densities being found at relatively low wind speeds. When correcting the abundance of particles > 700 µm for the effect of wind-induced mixing, Suaria et al., 2016 found a correction coefficient of 2.06 (max 8.97), resulting in an increased average concentration of particles/m^2 after correction. CTD rosettes can be deployed at the surface, and, providing all bottles are fired together, they can collect a volume of water that may be comparable to net samples. CTD bottles used in parallel with bucket sampling may provide a useful tool to sample microfibers in the surface and subsurface waters (Ryan et al., 2019).

Different count protocols for quantification of floating macrolitter have been proposed by Aliani et al., 2003; Ryan, 2013 modified in Ryan, 2014; Suaria and Aliani, 2014; and Strafella et al., 2019. The EU Joint Research Centre in Ispra organized a workshop in Barcelona in 2016 to define a standard for the sighting of microdebris. The identified methods were subsequently used in parallel during a common expedition in the Southern Ocean (Suaria et al., 2020a). The resulting recommendations were as follows: all floating debris items should be counted and recorded with a time assignment during daylight hours. Position data should be obtained through the vessel log. Metadata surrounding the items to be recorded include: size (estimated to the nearest 1 cm), perpendicular distance from the ship (m), buoyancy (at, above, or below the water surface), type of material (plastic, metal, glass, worked wood, paper-card, etc.), function (fishing gear, packaging, etc.), and color. Items can be further assigned to size categories (A. 2.5-5 cm, B. 5-10 cm, C.10-20 cm, D. 20-30 cm, E. 30-50 cm, F. > 50 cm) and to one of two major type categories: anthropogenic marine litter (AML) and natural marine litter (NML; Campanale et al., 2019; Suaria and Aliani, 2014). Data collection by this method is relatively simple and can be carried out from ships of opportunity as well as volunteers and in citizen science projects, following training. Training is a very critical step toward data quality when citizen science is used, but it is also relevant in field work activities carried out by scientists with limited experience in plastic sampling.

Subsurface and water column:

Sampling MP in the water column can be approached using vessels of opportunity or through targeted efforts. High volume pump samples have been shown to be very beneficial to collect large volume samples, and supplementary data can be collected simultaneously for comparison of results (see Lusher et al., 2015; Tekman et al., 2020). CTD rosettes can be used to collect water samples, but they may not be able to get large volumes. The volume of water required will be dependent on the presence of anthropogenic and organic items per sample. In the Arctic, a sample of 1 m^3 appeared to be sufficient when working with the underway pump systems (Lusher et al., 2015; Kanhai et al., 2018). Vertical nets (WP2) and bongo nets used for sampling zooplankton from the water column also have the possibilities to record MP: from 200 meters and up with a tow speed of 0.5 m/s, mesh size of 180 µm, and opening area of 0.25 m^2, sampled volume of 50 m^3.

Monitoring macrolitter in the water column is technically feasible, but not recommended in present day regular monitoring programs.

Table 2.4 Recommendations from international groups as well as an example of how such methods could be implemented in ongoing annual surveys in the Barents Sea.

	Guideline (level)			**Example:**
	GESAMP 2019 (UN)	Ministry of Environment Japan, Michida et al., 2019 (G20)	BASEMAN 2019 (JPI Oceans project)	Norwegian-Russian ecosystem survey in the Barents Sea
Manta - Tow duration - Mesh size	Recommended	20 mins,1-3 knots 0.3 mm	20 mins, 3 knots	15 mins, 3 knots 0.35 mm
Bulk water sample - Seawater intake - In situ pump	Feasible	N/A	N/A	Feasible
Niskin bottle (CTD rosette)	N/A	N/A	Vacuum filter directly onto GF paper	Possible dependent on volume
FerryBox	N/A	N/A	N/A	N/A
Visual survey	Recommended	N/A	N/A	Between stations, distance 35 nm
Vertical plankton nets (WP2)	N/A	N/A	N/A	Stations Fig 2.1

Sample processing

For methods related to sample processing, please refer to GESAMP, 2019 and Michida et al., 2019 for recommendations. Samples containing high levels of organic matter will need further processing before they can be analyzed for MP. Methods include digestion using bases or enzymes (acids are not recommended) and density separation. High temperatures and strong reagents are discouraged because they can affect plastic particles (Hurley et al., 2018; Lusher et al., 2020). Method choice is usually laboratory dependent. Any method used should be validated before use on samples to test spiked samples. Limitations of the methods must be reported to allow researchers to see the deviations from methods clearly.

Specific to the Arctic

There are currently no specific protocols available for the Arctic, although the relevant monitoring protocols for manta nets and pump samples are published in Lusher et al., 2015; Cózar et al., 2017; and Kanhai et al., 2018.

2.2.6 Quality assessment/quality control (QA/QC) specific to the compartment/matrix

For all investigations of MP in water samples, all sampling devices must be thoroughly cleaned before sampling, i.e., flushing with high volumes of filtered or ultra-pure water. Potential sources of contamination must be collected to act as a reference, including the clothing worn by samplers and any plastics used in the vicinity on the vessels, as well as vessel paint. Importantly, field blanks must always be collected. A field blank can include a filtered water rinse of a net (Michida et al., 2019) or an open moist (filtered water) sample container/petri dish for the same duration as handling of sample. Participation in workshops and ring tests to assure quality assurance/quality control (QA/QC), for example, through QUASIMEME is encouraged.

It must be noted that there is a great need to implement chemical characterization of fibers identified in surface waters. In a recent investigation of a global dataset of seawater samples, the majority of fibers were cellulosic (79.5%) or of natural origin (12.3%) whereas only 8.2% were synthetic (Suaria et al., 2020b).

An overview of QA/QC measures of MP sampling has been presented in Brander et al. (2020).

2.2.7 Existing monitoring for populations/contaminants in the Arctic

There are no current existing monitoring programs in the Arctic relevant to plastics in water samples. However, there have been several sporadic scientific investigations. The joint Norwegian-Russian ecosystem survey in the Barents Sea performed annually in August-October includes sampling of several fish species, shrimp, and sediments for the monitoring of contaminants. Floating debris and macrolitter as bycatch in trawls are recorded. Microplastics are collected from manta trawls from some of the stations (Figure 2.1).

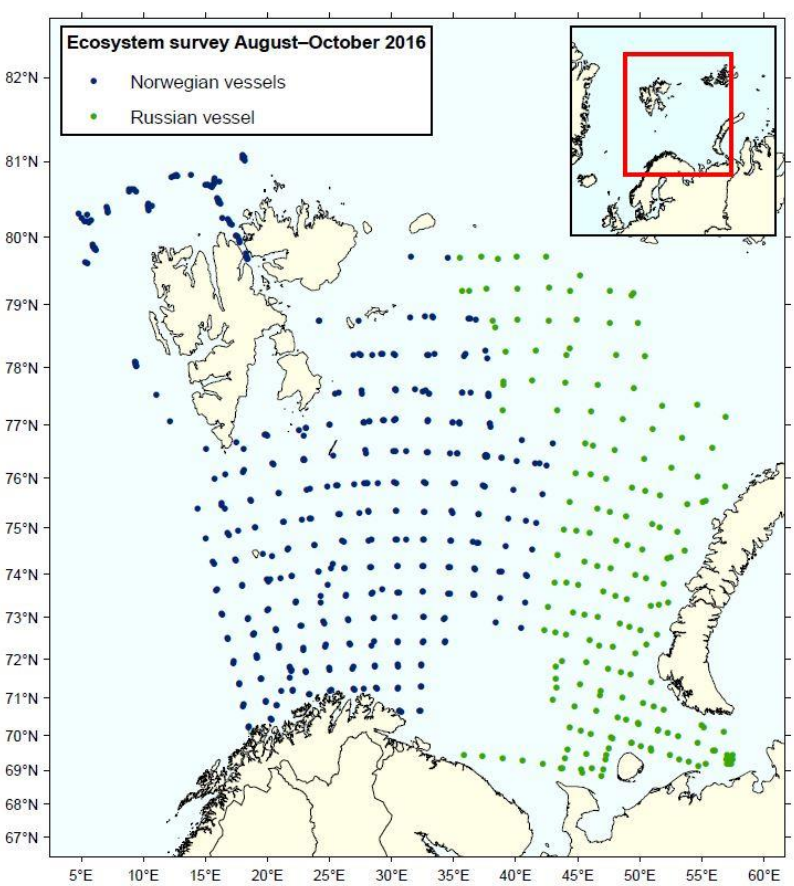

Figure 2.1 The joint Norwegian-Russian ecosystem survey in the Barents Sea performed annually in August-October includes approx. 300 stations.

2.2.8 Recommendations

In Table 2.5 below, the recommendations for monitoring and research are highlighted. It must be noted that to determine the frequency of sampling in terms of replicates per given sampling period, an assessment must be carried out in each region independently. For example, the sampling conditions as well as local conditions will dramatically affect the duration required for each sample. A power analysis should be carried out (with a minimum of 12 samples) per location to assess the variable plastic concentrations in a particular region. To this end, at the current level of data, it is not possible to determine the number of replicates or the number of stations required. This should become a priority for individual regions and should include an assessment by independent researchers who have no conflict of interest in the number of samples required.

In terms of frequency of surveys, it is recommended that sampling be carried out at a minimum on a yearly basis similar to the environmental monitoring for environmental contaminants. More intense sampling can be carried out if the aim is to assess seasonal variation, and to that end, sampling once per month, or once per quarter could be suitable.

Because net sampling is already commonplace and can provide harmonized data, it is recommended to continue this process while other methods are further validated. It is understood that this will focus on larger particles *300 µm and in so doing underrepresent the smaller-sized faction that are of interest in terms of understanding the impact or potential uptake by marine biota. Until further methods are explored, this is the method with the highest technological readiness level and it is already operational.

The volume of samples taken per sample will be heavily dependent on the sampling conditions during a particular survey; to account for this, the reporting of metadata is of upmost importance. Sampling can then be normalized for wave and windspeed. Thus, providing countries follow the same reporting system, data can be comparable.

Status of understanding for a representative sample:

Number of samples: requires further testing of statistical power.

Number of replicates: requires further testing of statistical power.

Number of field blanks: should be carried out in parallel to samples; ideally one field blank should be carried out in parallel to each collected sample. One method for field blanks is presented in Michida et al., 2019: here the net is cleaned thoroughly from the outside before the start of the sampling run to ensure no particles remain. The rinse water can be observed for particles. A second method is the exposure of dampened filter paper to the air while sampling is performed. This should give an indication of the number of airborne particles.

Table 2.5 Summary of monitoring and research recommendations for water samples.

	1st level (must do)	**2nd level (should do)**
Monitoring	Net samples (water surface of coastal, freshwater, and fjord; 300 µm mesh) (Volume will be variable and dependent on sampling conditions) Large pump - selected offshore locations (sequential filtration, e.g., 1 mm, 300 µm, 100µm) collected subsurface – 1-7 meters, 1 m^3 per sample	Large volume pump samples volume (sequential filtration, e.g., 1 mm, 300 µm, 100 µm) Subsurface – 1-7 meters, 1 m^3 per sample
Research	Offshore net samples Visual surveys	Large pump - inshore, 1 m^3 per sample from surface waters Visual surveys supported by communities including opportunistic observations from marine mammal observers, fisheries observers, and fishers

Table 2.6 Summary rationale for recommendations, including estimated costs for implementing programs; 0 – litter and plastic pollution monitoring already in place with regular funding; $ - relatively inexpensive because new litter and microplastic monitoring programs can use existing programs to obtain samples in at least some regions, but need to have some additional capacity to process samples for litter and plastic pollution; $$ - either sampling networks and/or capacity need to be developed to monitor litter and microplastic pollution; $$$ - development of sampling networks, processing capacity of samples, and reporting all need to be developed in the majority of the Arctic regions.

Recommendation	**Program Cost**	**Rationale**
Primary Recommendations		
Coastal: Net sampling ≥ 300 µm - Routine monitoring surveys can be adapted - Easier to adapt to weather conditions in coastal areas	$	Existing research programs are already in place conducting routine surveys making it relatively easy to add a collection for plastic pollution to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring to cover the costs of sampling. Processing will require additional costs.
Offshore: pump samples - Routine monitoring surveys can be adapted - Less challenging to use pumps in offshore waters	$	Existing research programs are already in place conducting routine surveys making it relatively easy to add a collection for plastic pollution to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring to cover the costs of sampling. Processing will require additional costs.
Secondary Recommendations		
Inshore: pump samples - Routine monitoring surveys can be adapted	$$	Existing research programs are already in place conducting routine surveys making it relatively easy to add a collection for plastic pollution to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring to cover the costs of sampling. Processing will require additional costs and sequential filtering is more time consuming.
Subsurface sampling - Routine monitoring surveys can be adapted	$	Existing research programs are already in place conducting routine surveys making it relatively easy to add a collection for plastic pollution to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring to cover the costs of sampling. Processing will require additional costs.

2.2.9 Knowledge gaps and research priorities

Box A: data needs/expectation	**Auxiliary data**
Must have data • Location • Date • Collection method • Depth • Volume of sample (including original volume and subsampled volume • and any analysis on variance between subsamples) • Number of particles • Auxiliary environmental data • Polymer type (mandatory for at least a subsample > 300 µm) **Nice to have for all data** • Color • Size category (> 1 mm, 1 mm-300 µm, 300-100 µm, < 100 µm) • Morphological information (shape) • Polymer type	• Wind speed and direction • Sea state • Depth in case of seawater from rosette • Proximity to coastal, river streams and/or estuaries • Proximity to wastewater treatment plants

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Water sampling.

2.3 Monitoring of microlitter in aquatic and shoreline sediments

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2.3.1 Introduction

Sediments, both freshwater and marine, act as sinks for microplastics (MP) whether due to rapid sinking of high-density plastic particles (Woodall et al., 2014; Kowalski et al., 2016; Erni-Cassola et al., 2019), settling caused by biofouling (Kaiser et al., 2017; Rummel et al., 2017), or incorporation in sinking organic aggregates, e.g., marine snow (Porter et al., 2018; Zhao et al., 2018). Settled MP particles may subsequently be resuspended and further transported with water currents to settle in calmer areas with finer sediments far away from their source (Enders et al., 2019). Because sediments in calm areas accumulate and sequester deposited MP, they provide a temporal record of MP input to the aquatic environments and thus also constitute a relevant matrix for monitoring. Experimental studies show weak upward transport of already buried MP (≥ 100 µm) in marine environments (Näkki et al., 2019), which further stresses the importance of sediments as a sink for MP.

Particles (fragments and fibers) can have low or high densities; those with low density (buoyant) can be transported from point sources such as wastewater outlets to shallower areas and settle in shoreline sediments and beach sand (Lots et al., 2017; Bosker et al., 2018; Piñon-Colin et al., 2018). Shorelines constitute the interface between land and sea, and function as dynamic repositories for MP originating both from the sea and from weathered and fragmented stranded macrolitter. Aided by wind, wave, and tidal action, MP on beaches will be incorporated in deep sand layers (Turra et al., 2014) and be transported higher up on the back shores (Zhang, 2017). The high energy environment creates patchiness (Fisner et al., 2017) and the temporal record of beach sand and shoreline sediments is more difficult to interpret because of the dynamic nature of these environments.

2.3.2. Status of global science

The scientific literature on MP in sediments shows great variation in the use of methods for sampling, extraction, and detection, as well as the lowest particle size limit used for detection. These differences obscure direct comparisons between investigations. Studies also report on great differences in MP concentrations between sites in populated areas such as the North East Atlantic. For example, in studies carried out in Byfjorden outside Bergen, Norway and at locations in the southern North Sea, the same methods and the same size limit (>11 µm) were applied. In the Norwegian fjord, concentrations were found to vary between 12,000 and 200,000 particles kg^{-1} dry weight (dw) sediment, whereas concentrations varied between 3 and 1,189 particles kg^{-1} dw in southern North Sea sediments (Haave et al., 2019; Lorenz et al., 2019). The highest levels of MP detected in Arctic sediments are reported from Canada where concentrations of particles in the size range 53-2000 µm were found to vary between 0 and 16,000 particles kg^{-1} dw at 20 locations (Huntington et al., 2020). Most other Arctic studies report considerably lower concentrations.

Literature on freshwater sediments is limited, however, recent modeling (Besseling et al., 2017) and field studies (Hurley et al., 2018a) show that freshwater sediments may hold a substantial fraction of the world's MP pollution. Mjøsa Lake in Norway was recently investigated for the presence of MP in sediment cores, assessing the influence of sources and deposition. The highest MP values were reported near urban areas (7,310 MP particles kg^{-1} dw) and main roads (3,890 MP particles kg^{-1} dw; Lusher et al., 2019).

2.3.3 Current levels in the Arctic

Microplastics detected in the Arctic may derive from distant sources, having been transported there with sea currents (Lusher et al., 2015; Cózar et al., 2017; Tekman et al., 2020) or by air (Bergmann et al., 2019). Arctic MP pollution may also originate from local sources including: (1) wastewater and land-based waste storage (Granberg et al., 2019; von Friesen et al., 2020), (2) intentional littering, (3) dumping of sewage or garbage from ships, and (4) lost fishing gear (Tekman et al., 2017). In addition, sea ice can be considered as a secondary MP source (Obbard et al., 2014; Peeken et al., 2018; von Friesen et al. 2020). The relative importance of local and distant sources is poorly investigated and because wastewater treatment and waste management are poor in the Arctic, local sources or pathways may be underestimated.

Microplastics have been detected in all parts of the Arctic, even in sediments from the Arctic Central Basin (Kanhai et al., 2019). It is important to recognize that any comparisons between studies will be tainted by the fact that the methodology used varies greatly, which in turn will affect numbers, sizes, shapes, and polymeric composition of the MP particles reported. With this in mind, the highest reported concentrations in the Arctic, ca. 10,000–16,000 (size 53-2000 µm) MP particles kg^{-1} dw, were found at two locations in Eastern Canadian waters (Huntington et al., 2020). These two sites seem to be extreme hotspots because the concentrations at 17 of the 20 locations included in this study were between 0 and 2,000 particles kg^{-1} dw. Tekman et al., 2020 also detected high concentrations of MP (size ≥ 11 µm) ranging between 239 and 13,331 particles kg^{-1} dw in sediment samples collected at five stations of the HAUSGARTEN observatory in the Fram Strait. However, sediments collected at the same sites a year before by Bergmann et al. (2017) showed considerably lower concentrations, ranging between 42–6,595 particles (≥ 11 µm) kg^{-1} dw, with concentrations exceeding 4,000 MP kg^{-1} dw at 8 out of 9 sampling stations. The MP concentrations were found to correlate both with higher concentrations of macrolitter and with chlorophyll *a* (Bergmann et al., 2017), which indicates that this area is an accumulation site for both large plastics and fresh organic matter from the pelagic photic zone or the sea-ice edge. In the deep sea, all bottom types (accumulation and transport bottoms) occur as they do in shallower areas, and MP concentrations are thus expected to vary accordingly.

Arp et al., 2018 detected between 0 and 3,189 MP particles (≥ 45 µm) kg^{-1} dw in sediments from the Barents Sea. Mu et al., 2019 also detected MP in sediments collected in the Bering and Chukchi Seas and found that 6 out of 7 investigated sites were polluted with MP (size unspecified) varying from 0 to 69 particles kg^{-1} dw. It is likely that MP concentrations in Arctic sediments are low in general with hotspots related to specific sources or hydrodynamic conditions. The deep-sea area around the HAUSGARTEN observatory is special in that it receives particulates released from the melting Arctic sea-ice front (Bergmann et al., 2017; Tekman et al., 2020). One of the areas in the Canadian Arctic with very high MP concentrations was also located by a glacier (Huntington et al., 2020). Sea ice is known to contain high amounts of MP released during summer melting (Obbard et al., 2014; Peeken et al., 2018; von Friesen et al., 2020), and glacier ice and snow have been shown to contain plastic particles, likely originating from atmospheric deposition (Ambrosini et al., 2019; Bergmann et al., 2019; Evangeliou et al., 2020). Very little is yet known about relative contributions from sources for MP in coastal Arctic marine sediments. Granberg et al., 2020 measured MP near and far from local pollution sources in coastal marine sediments around Sisimiut, Greenland and in Kongsfjorden-Krossfjorden, Adventfjorden, and Grønnfjorden, Svalbard. Microplastics were found at all sites, with higher concentrations close to pollution sources. However, high concentrations were also found at single sites classified as pristine in Greenland. Here, MP particles were identified as originating from fishing gear.

Information regarding plastic pollution in Arctic freshwater sediments is vastly lacking. One study was conducted in Ny-Ålesund, Svalbard reporting a dominance of fibers (González-Pleiter et al., 2020). Luoto et al., 2019 also reported on an increasing abundance of MP in Lake Revvatnet, Hornsund, Svalbard. The increase of MP was hypothesized to result from climate change, both through an increase in meltwater inflow into the lake and a higher prevalence of nesting seabirds, little Auks or Dovekies (*Alle alle*), collecting MP at sea and depositing them in the lake with their guano.

2.3.4 Benefits of using sediments as a plastic monitoring matrix

Sediments are highly suitable for MP monitoring because they constitute a time-integrated sink for all types of particles and aggregates including plastics (Soutar et al., 1977; Erni-Cassola et al., 2019). This is analogous to more established monitoring protocols for organic contaminants and metals in the marine environment. Shoreline sediments and beaches offer easy access and cost-effective options for MP assessment and monitoring.

2.3.5 Limitations to using sediments as a plastic monitoring matrix

Whether the objective of a monitoring program is to follow time trends or to target specific sources of MP pollution in marine sediments, it is essential that sampling be carried out at locations where MP settle and accumulate rather than in areas with sediment erosion or transportation. Our knowledge regarding MP fate processes is still limited, which makes it difficult to pinpoint locations of MP accumulation. Some studies show correlations between MP and sediment grain size and/or organic matter content (Strand et al., 2013; Vianello et al., 2013; Enders et al., 2019; Haave et al., 2019), whereas other studies find no such correlation (Alomar et al., 2016; Peng et al., 2017). In a large-scale, meta-analysis, Erni-Cassola et al., 2019 showed a high general accumulation of MP in intertidal sediments. Deep-sea sediments have also been suggested as a sink for MP and (accordingly) the highest concentrations ever recorded in marine sediments were found in deep-sea sediments from the Fram Strait (Bergmann et al., 2017). In general, particles of various kinds, i.e., phytoplankton cells, zooplankton faecal pellets, detritus, and fine-grained mineral particles, settle in calm areas and form soft sediment accumulation bottoms. This is where organic matter and sediment associated contaminants accumulate and are generally monitored. Considering the characteristics of many MP particles, settling in this type of area is a likely fate.

Microplastics may be incorporated in marine aggregates formed mainly by algae and detritus (Zhao et al., 2018). These aggregates (often referred to as marine snow) have high sinking velocities and are presumed to be important vehicles for the transportation of small particles from the surface to the bottom. Furthermore, intertidal sediments are generally high in organic matter, and Bergmann et al., 2017 found correlations between MP and chlorophyll *a* concentrations (indicative of settling phytoplankton) at their deep-sea site. Finding the right spot for MP monitoring will thus require knowledge of and/or initial screening of the area, and preferably hydrodynamic modeling to target calmer areas where particles are likely to settle.

Marine sediments are highly heterogenous when it comes to composition and abundance of benthic fauna and flora, resulting in a high degree of spatial and temporal patchiness. Patchiness is a factor to consider in relation to field sampling of MP both under water and along shorelines (Fisner et al., 2017; GESAMP, 2019; Korez et al., 2019). Both patchiness and temporal variations in MP occurrence become serious complicating factors due to changing environmental conditions and strong forces acting on beaches (Fisner et al., 2017). These factors are likely accentuated in the harsh Arctic environment. The level of patchiness will determine the number of replicates necessary to collect to obtain sufficient statistical power.

2.3.6 Methods

There are at present no standardized protocols for monitoring MP in submerged sediments. There is, however, extensive, existing, and transferable knowledge from other sediment monitoring approaches. Two approaches are relevant when monitoring time trends for MP pollution in sediments: (1) recurrent sampling of the recently accumulated surface sediment layer, and (2) retrieving cores from varved undisturbed sediment and subsequent slicing of the cores into geologically dated sections. Geological dating can be achieved using radionuclide techniques. Number one is the most common approach for other sedimentary parameters and will be the focus here.

Concerning shoreline and intertidal sediments, GESAMP, 2019 developed guidelines for MP monitoring, and we recommend applying these to monitoring MP on shorelines and beaches in the Arctic. These guidelines also address obstacles arising when sampling MP on, e.g., rocky shores and shores of varying geology. The methodological difference between assessing MP content in underwater and shoreline sediments mainly concerns sample collection. The subsequent steps are applicable for both matrices. Key points regarding sample collection of shoreline sediments will be addressed here. For details, the reader is kindly referred to the GESAMP, 2019 report.

Sample collection: aquatic sediments

Submerged sediment can be sampled using any type of box or cylinder corer designed to collect sediment samples while keeping an intact, undisturbed sediment surface. The number of grabs or core samples required to achieve a sound statistical dataset will depend on the level of contamination and the patchiness or heterogeneity of the sediment. Low levels of contamination and high patchiness will lead to great variation in numbers of plastic particles retrieved kg^{-1} dw sediment. If the number of MP is low, the sample size must be larger, i.e., more sediment must be sampled. Individual samples from different cores or grabs collected within the same area can be pooled to obtain a large enough sediment sample. Pooling will also reduce the influence of sediment heterogeneity or patchiness. Furthermore, the number of particles in a given sample volume decreases with the increasing particle size. There will thus be more 10 µm particles than 300 µm particles in a sediment sample. This means that the sediment sample must be larger when aiming for large-sized particles. Sediment samples between 30 and 500 g wet weight (ww) have been suggested. For larger particles (> 300 µm), sediment samples larger than 500 g ww might be needed. The number of particles in the blank samples define the detection limit for each collected sample and MP concentrations below that of the blanks should hence be considered as being below the detection limit. The level of contamination must thus be monitored at all steps of sampling and sample treatment. The most informative and sustainable way to design a sediment monitoring program with sound statistics is to gain insight into the variation between samples collected in the area of interest. A power study is useful when aiming to optimize the sampling statistics.

Only the recently accumulated sediment layer (usually 1-2 cm in coastal areas) should be retrieved from each core or grab sample. Surface sediment should be collected using a metal device rinsed in filtered MQ water (see QA/QC section) and transferred to pre-rinsed and aluminium foil covered, lidded, and marked glass jars (see QA/QC section). Samples should be stored cold or frozen (-20 °C) and dark until extraction and analysis. How deep the recently accumulated sediment layer extends depends on both physical and biological conditions of the sampling area. The deposition rate of MP and the mixing depth of the particles into the sediment is affected by natural factors like currents and bioturbation (burying and excavation of sediment associated fauna) but also by anthropogenic activities, e.g., trawling, dredging, and other physical disturbances resulting in resuspension events. In areas with low sedimentation rates, e.g., in offshore regions or in lakes, the mixing depth of MP may be even less than one cm (Martin et al., 2017; Lusher et al., 2019). It is thus essential to be highly familiar with conditions at the sampling site. In areas with high sedimentation (e.g., near glacier fronts) and/or deep bioturbated layers, sampling can be performed using only a grab sampler, as long as the sediment surface is clearly distinguishable.

Sample collection: shoreline sediments

The geology of shorelines varies from wide mud flats to steep rocky shores. Methods developed for monitoring MP on sandy beaches or mudflats are not applicable to broken coastlines with mixed substrates (McWilliams et al., 2018; GESAMP, 2019). McWilliams et al., 2018 found that the presence of rocks has a great impact on the distribution of MP in Arctic beach sand and sediments calling for a nuanced sampling strategy. Shoreline and beach sediments are commonly sampled along a transect perpendicular to the waterfront. Along this transect, with discrete distance increments from the waterline, replicate samples are collected by throwing a one m^2 quadrat and then retrieving the uppermost five cm of the sediment for MP analysis (GESAMP, 2019; MSFD, 2020). McWilliams et al., 2018 found that MP were buried further into the sediment around rocks on Arctic beaches, and Turra et al., 2014 found microlitter buried down to at least two meters in sandy beaches. Based on this knowledge, it may be useful to perform stratified sampling in which samples are collected every five cm down to a specific depth. It is, however, unclear how depth distributions of MP on beaches should be interpreted. Because microlitter is patchily distributed on and in shoreline and beach sediments, replication is important. MSFD, 2020 recommends collecting five replicate samples. However, as previously described for submerged sediments, the most informative and sustainable way to design a shoreline sediment monitoring program with sound statistics is to first gain insight into the variation between samples. For this, a pilot study needs to be designed with the aim of optimizing statistical power and only then the accurate number of replicates can be determined. Other concerns related to sediments regarding sample size, particle numbers, procedural blanks, and control samples presented above are applicable to shoreline and beach sediments as well.

Sample treatment

Microplastic particles must be separated from the sediment matrix prior to analysis. For this purpose, several methods are applied and a number of reviews have assessed the pros and cons of different methods (Hidalgo-Ruz et al., 2012; Rocha-Santos and Duarte, 2015; Van Cauwenberghe et al., 2015; Miller et al., 2017; Mai et al., 2018; Stock et al., 2019) but there is still no consensus or a standardized protocol. Instead, quality criteria for the applied method have been put forward (e.g., Setälä et al., 2019) including procedural steps to be fulfilled. The quality criteria imply proving that the method chosen: (1) does not harm the plastic polymers, the environment, or humans; (2) that the recovery rate of MP particles likely to be found in a field sample, i.e., particles of different polymers, different shapes, etc., should be tested, verified, and reported; and (3) that contamination is minimized, controlled, and reported. Suggestions for generalized protocols include sieving, density separation, and digestion of the organic matrix.

Sieving sediment samples initially is useful to remove large stones and debris or to collect larger plastic fragments. When sieving is carried out in situ there is limited contamination control. This approach is not adequate for small MP (< 1 mm) and isolation steps must be performed under laboratory conditions. Care should also be taken not to further fragment brittle particles. Procedural controls should be introduced (see QA/QC).

Dissociation and digestion of the organic matrix can be performed using established methods including pre-treatment with detergent and/or degradation using enzymatic, oxidizing, and/or alkaline treatments. Sodium dodecyl sulphate (SDS) or sodium lauryl sulphate (SLS) are detergents and protein denaturants used as a primary step to release plastic particles from the organic matrix in sediments. Organic matter degradation can be achieved using enzymes, either alone (Setälä et al., 2019; von Friesen et al., 2019) or in combination with oxidizing agents (Löder et al., 2017). Degradation using natural pancreatic enzymes (amylase, protease, and lipase) has been shown to be a simple and efficient method that is mild and non-destructive to plastic polymers (Piarulli et al., 2019; Setälä et al., 2019; von Friesen et al., 2019). Other protocols use sequential enzymatic treatments, which can be just as efficient but may require change of pH and extensive amounts of time (e.g., Löder et al., 2017). Oxidizing agents such as H_2O_2 as a stand-alone digestion method require cooling and a reduced concentration. Using H_2O_2 with an iron catalyst, i.e., Fenton's reagent, will speed up the oxidization process and is therefore effective in digesting samples rich in organic matter (e.g., sewage laden sediments) that may be challenging to digest. This procedure should be performed with the understanding that sample loss and discoloration of MP may occur because the reaction is highly exothermic and even volatile, quickly reaching temperatures above 100 °C (Hurley et al., 2018b; Munno et al., 2018). To ensure that temperatures do not reach above 40 degrees and plastics start melting, ice baths have been routinely used (e.g., Hurley et al., 2018b). Alkaline solutions, often KOH, can be used either alone or alternatively in combination with the oxidizing agent NaOCl (Strand and Tairova, 2016) because this seems to have only little impact, if any, on most common plastic materials (Enders et al., 2017). Acid digestion is sometimes proposed as a digestion method but has been found to damage and destroy certain polymers. The Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), an advisory body for the United Nations system on the scientific aspects of marine environmental protection, has explicitly recommended that acids should not be used for this purpose (GESAMP, 2019).

Density separation is used to separate heavy mineral particles from lighter plastics once the organic matrix is degraded. Commonly used saline solutions for density separation from sediment are zinc ($ZnCl_2$) and sodium iodide (NaI) both with saturated solution densities above 1.85 g cm^{-3}, sodium polytungstate ($Na_6H_2W_{12}O_{40}$, saturated density: 3.1 g cm^{-3}), and sodium chloride (NaCl, saturated density: 1.2 g cm^{-3}; see for e.g., Ng and Obbard, 2006; Claessens et al., 2013; Bergmann et al., 2017). A less common alternative to density separation is to extract the MP with oil-water separation (Crichton et al., 2017; Mani et al., 2019). The technique is based on the oleophilic nature of plastics, i.e., plastics have a strong affinity for oils. A number of different devices have been designed to aid in density separation including elutriation towers (Claessens et al., 2013), pressurized fluid extraction systems (Fuller and Gautam, 2016), density separation towers (Imhof et al., 2012), and traditional separation funnels. After separation, the top layer is decanted/retrieved and plastic particles collected on filters with a desired mesh or pore size. These filters may be subjected to further chemical or enzymatic treatment to remove remaining organic matter. A saline solution with a density > 1.5 g cm^{-3} is required to capture the majority of MP polymers, e.g., polyurethane (PU, 1.3 g cm^{-3}), polyvinyl chloride (PVC, 1.4 g cm^{-3}), and polyethylene terephthalate (PET, 1.4 g cm^{-3}).

Dry weight of sediment is estimated according to general US EPA and NOAA practices. The sediment is thoroughly homogenized and three aliquots of approximately 1 to 2 g are collected, weighed, and then dried at 105 °C to a constant weight. The weight of the dried aliquot is the dry weight of the sample. Percent moisture is determined by calculating the amount of weight lost during the drying procedure.

2.3.7 Quality assurance/quality control (QA/QC) specific to the compartment/matrix

All methods should use appropriate monitoring of procedural and airborne contamination. Quality assurance/quality control (QA/QC) should be followed from sample collection to data reporting and analysis. During sampling collection, efforts to prevent contamination should be enforced and all steps taken to facilitate this should be clearly reported. Blanks should be carried out in the field and in the laboratory.

Particle recovery/recovery efficiency should be tested for all methods alongside sampling. These can include standard reference materials, matrix spikes, and positive and negative controls (Brander et al., 2020). It is also important to minimize the number of steps and the open exposure of the sample to avoid contamination risks.

Data from field samples should be adjusted to procedural blanks. Unless MP particles in the blank samples are obviously different to any particles found in the field, sample corrections should be carried out either using blank correction or the degree to which sample values exceed the limits of detection (3 x standard deviation, SD, of mean concentration detected in procedural blanks) or limit of quantification (10 x SD). If the blank samples contain MP particles that clearly and without any doubt differ from any particles detected in the field samples, these particles may be ignored. Furthermore, the percentage of particles confirmed as plastic/synthetic/anthropogenic should be clearly reported, as should the levels of uncertainty in data output.

Box A: Data needs/expectations.

Must have data for reporting microplastics in sediments

- Location, including latitude and longitude
- Date, including day, month, and year
- Sampling method (type of box corer, cylinder corer, grab)
- Sampling depth (sea depth, m)
- Sample size (kg, g wet weight)
- Wet weight/dry weight relationship
- Total number of (sub)samples per site (i.e., n) and if individual samples were pooled
- Storage after sampling
- Method for organic matter dissociation and digestion with documented impact on plastic polymers
- Method for separation with documented recovery rate of relevant polymers and size classes
- Filter type and pore/mesh size used
- Average (with standard deviation) number of MP particles as determined by visual analysis reported in size categories 5- ≥1 mm and 1000- ≥ 300 µm
- For each particle, category (i.e., fragment, pellet, fiber/line, film, foam, or other), size, shape, and color (reported in eight broad color groups) must be recorded in accordance with GESAMP (2019)
- Polymer ID must be determined and documented for at least a subset of relevant/representative particles within the visually identified size category 1000- ≥ 300 µm

Beneficial to have for all data

- Mass of MP (determined by, e.g., pyrolysis–gas chromatography–mass spectrometry, Pyr-GC/MS, or estimated from surface area of particles)
- Granulometry, e.g., grain-size fractions < 2 mm and < 63 µm
- Sediment organic matter content (total carbon (TC)/total organic carbon (TOC))
- Vicinity to potential sources

2.3.8 Existing monitoring for sediments/contaminants in the Arctic

Linking MP sampling to already existing monitoring programs is advantageous because other ancillary parameters relevant for MP monitoring will be measured at the same time, e.g., sediment granulometry, organic matter content, etc. The Norwegian monitoring program, Mareano, could be suitable for linked MP monitoring of marine sediments. It covers the northern Norwegian coastal and offshore areas including the Barents Sea (Figure 2.2) and is coordinated by the Institute of Marine Research in collaboration with the Geological Survey of Norway and the Norwegian Hydrographic Service. Further, the Norwegian Environment Agency facilitates a number of monitoring programs focusing on environmental contaminants in sediments, has (2021-) requested the inclusion of MP, and it is currently out to tender. The German Alfred Wegner Institute (AWI) regularly visits the deep-sea observatory HAUSGARTEN in the Fram Strait. Here sediments are sampled for various scientific purposes including MP pollution. Whether there are any other ongoing Arctic monitoring programs that continuously sample sediment is unclear.

2.3.9 Recommendations

- Sediment should be collected where particles are likely to settle, i.e., on accumulation bottoms and not on transport or erosion bottoms.
- Do not apply temperatures above 40 °C to the samples at any time of preparation. Above this temperature, polymers like rayon lose their tenacity and the structure is modified.
- Test all methods for extraction efficiencies and harmfulness to plastic polymers in laboratories before use.
- All digestive agents must be prepared and filtered through filters with a smaller pore size than the lowest desired particle detection limit of the sample to remove impurities and to prevent the introduction of contamination into samples.
- Salt solutions for density separation must be prepared and filtered through filters with a smaller pore size than the lowest desired particle detection limit of the sample to remove impurities and to prevent the introduction of contamination into samples.
- A solution with a density of 1.6 g cm^{-3} is recommended for separation to enable comparison between studies. NaI is identified as the most suitable density separation solution in terms of hazards, extraction efficiency, and recyclability. Other extraction solutions can be used as long as they reach a density of 1.6 g cm^{-1} and are similar or better regarding the selected quality criteria.
- Repeated extraction is recommended, and samples should be thoroughly mixed following the addition of salt solutions (Hurley et al., 2018b). The number of repeats is sufficient when particle numbers retrieved are no higher than background levels.
- Flotation as a method for particle separation should not be performed on small size fractions where bubbles may interfere with the flotation process; however, flotation may be suitable for large size fractions (Nguyen et al., 2019).
- It is advisable to use a laminar air flow bench or similar when samples are exposed to air.
- Procedural controls are extremely important for all steps of the sample preparation procedure, i.e., sampling, transport, digestion, extraction, and filtration (Brander et al., 2020).

2.3.10 Research gaps

There is still a lack of data and information regarding MP fate and patchiness in sediments, which makes it difficult to provide solid advice on the number of replicates required to support robust statistical analyses. When setting up a monitoring program, it will therefore be important to first investigate the hydrodynamics of the area and identify accumulation zones and patchiness of sediment associated MP.

Due to the lack of established methodology, it is not possible to advise on the monitoring of MP particles smaller than 300 µm. This lower size limit is thus not based on ecological or ecotoxicological relevance. There is a great desire to be able to routinely sample much smaller MP and even nanoplastic fractions.

Table 2.6 Summary of monitoring and research recommendations for litter and microplastics monitoring in Arctic sediments.

	1st level (must do)	**2nd level (should do/develop)**
Monitoring	- Visual analysis of microlitter content including categories for shapes and color in surface sediments from accumulation bottoms. All microlitter should be monitored and reported in size categories 300 µm – 1 mm and 1-5 mm. - Analysis on polymer ID of a selection of relevant microlitter particles ≥ 300 µm.	Point source studies. - Visual analysis and polymer ID of microlitter particles ≥ 100 µm.
Research	- Automated analysis on polymer ID of microlitter < 100 µm. - Determination of deposition areas and MP fate processes. - Mass-based units for MP contents. - Strategies for sampling shoreline and beach sediments for MP analysis.	

Table 2.7 Summary rationale for recommendations, including estimated costs for implementing programs: 0 - already in place; $ - relatively inexpensive because of synergy with other projects but needs to have some additional capacity; $$ - either networks and capacity will need to be developed; $$$ - development of sampling networks, processing capacity, and reporting all need to be developed.

Recommendation	**Program Cost**	**Rationale**
Surface sediments analyzed for all microlitter particles ≥ 300 µm. - Useful for monitoring, in alignment with OSPAR, MSFD. - Accumulation bottoms are temporal records of plastic pollution.	$$	Monitoring programs are already in place for sediments regarding pollutants, trophic status, and biota, making it easy to include sampling for MP. The main cost involves processing and analysis of samples, which can be quite costly.

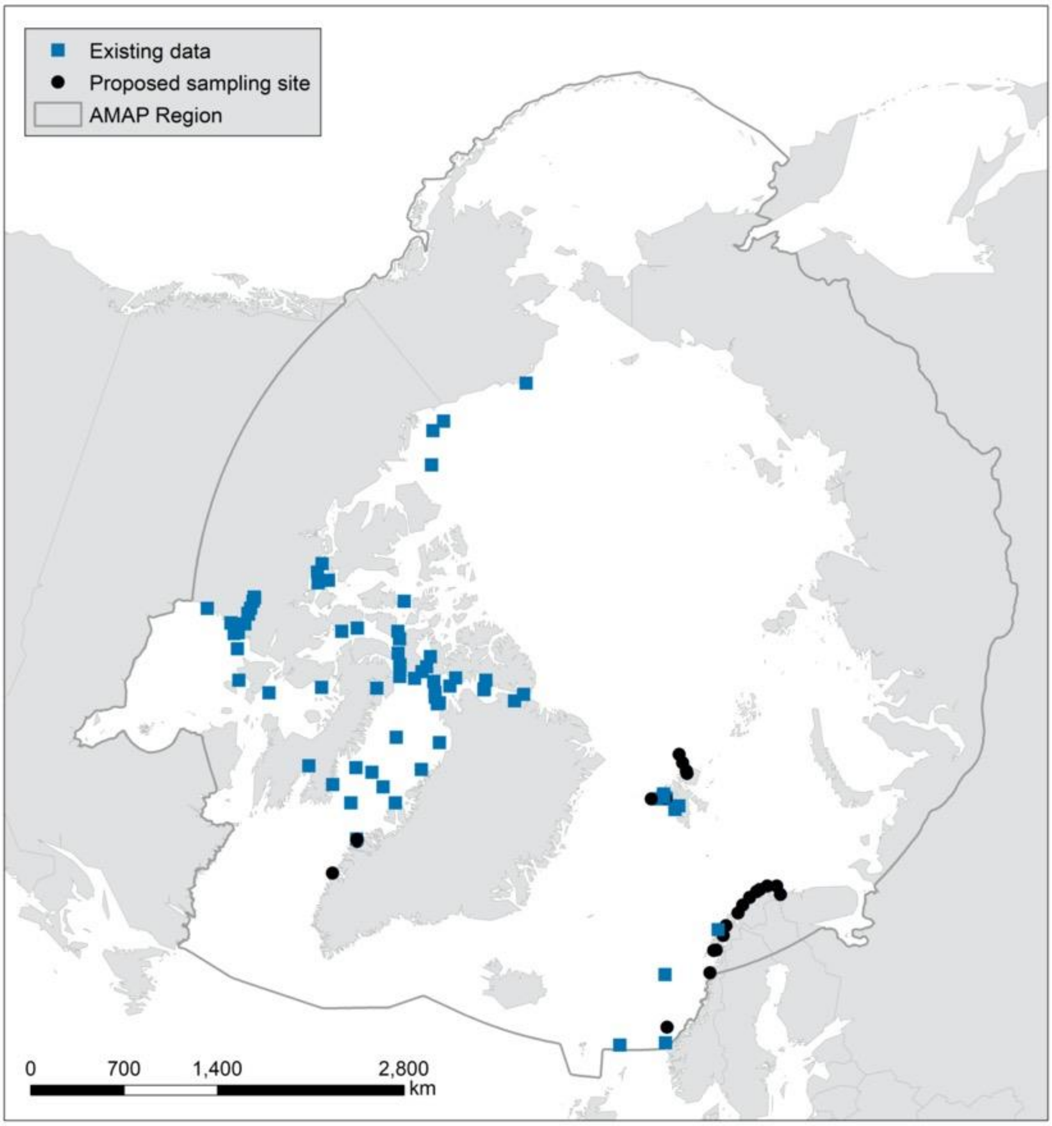

Figure 2.2 Map of existing and proposed sampling sites for MP in marine sediments within the AMAP region. Existing sampling sites refer to sites where there are data on MP concentrations in sediments. The HAUSGARTEN underwater observatory regularly visited by German Alfred Wegner Institute cruises is not marked on the map.

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Plastic sediment sampling in Iqaluit, Nunavut, Canada.

2.4 Terrestrial soils

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2.4.1 Introduction

Plastic pollution is present in terrestrial soils but in comparison to other abiotic and biotic compartments, relatively little research has been carried out on microplastics (MP) pollution in soils (reviewed by Bläsing and Amelung, 2018; Wang et al., 2020; Zhang et al., 2020). This lack of research is particularly true for the Arctic where, at the time of writing, no peer-reviewed studies existed for MP pollution in terrestrial soils in Arctic environments. Therefore, much of this section focuses on the findings of plastic pollution research in terrestrial soils in other environments. However, MP pollution in soils, as a whole, remains highly understudied compared to other abiotic and biotic compartments (Wang et al., 2020).

Microplastic pollution in terrestrial soils may occur through a variety of pathways including sewage sludge applications (Corradini et al., 2019), biotic vectors (Provencher et al., 2018), the breakdown of plastics used in agriculture (Piehl et al., 2018), and (long-range) atmospheric deposition (Allen et al., 2019), among other pathways. However, no data on MP in terrestrial Arctic soils exist. The mobility of MP in soils, both vertically along a soil depth profile and horizontally along the soil surface, is still an area that requires further research (Wang et al., 2020), however, it has been estimated that upwards of 99% of MP applied to agricultural fields from sewage sludge likely enter aquatic environments through erosion and surface runoff (Crossman et al., 2020). This mobility of MP in terrestrial soils has not been studied in Arctic environments and may be very different than what has been reported in temperate agricultural systems for numerous reasons including the presence of permafrost, differing vegetation cover, and land management practices. Therefore, there is a great need to understand the presence, concentration, composition, and fate of MP in Arctic soils to obtain a clearer overview of MP compartments and plastic cycling in the Arctic. Furthermore, we know little of the potential degradation of MP in soils and how terrestrial soils potentially link the atmospheric and aquatic pools of MP.

There is limited data on the potential impact MP have on terrestrial environments and no research in Arctic environments where soil conditions and fauna can differ greatly from more southern regions. Recent studies in more southern environments have shown some impacts of MP (reviewed by Guo et al., 2020) in soils on biota including earthworms (Zhu et al., 2018; Wang et al., 2019), snails (Song et al., 2019), and crops (Qi et al., 2018; de Souza Machado et al., 2019). Microplastics in soils have also been noted to change soil enzymes (de Souza Machado et al., 2019) and microbial biomass (Awet et al., 2018). Further research is required, however, to understand what impacts, if any, MP pollution is having on soil ecosystems (Guo et al., 2020; Wang et al., 2020), particularly in Arctic environments where no data yet exist.

Monitoring MP in terrestrial soils in the Arctic would provide information on the current abundance and spatial distribution of MP pollution in soils and over time provide data on long-term trends in plastic pollution in the Arctic. These data would be useful in teasing apart long-range versus local sources of plastic pollution to the Arctic and provide information on a key compartment and potential cycling of plastic pollution in Arctic environments.

2.4.2 Existing monitoring frameworks for microplastics in terrestrial soils

At present there are no standardized protocols for the monitoring of MP in terrestrial soils (Qi et al., 2020; Wang et al., 2020; Xu et al., 2020). Because of the paucity of research on plastic pollution in terrestrial soils, little information is available on best practices for monitoring plastic pollution in soils, including in Arctic environments (Bläsing and Amelung, 2018; Wang et al., 2020). Methodology for sampling MP in soils is driven largely by the research question at hand including the depth of sampling and the quantity of soil sampled (Möller et al., 2020; Zhou et al., 2020). General recommendations typically suggest following similar procedures to aquatic sediments, however, more research is required to ensure that the optimal protocols are put in place for monitoring plastic pollution in terrestrial soils in the Arctic. It is anticipated that more formal protocols for monitoring MP in soils will be developed over the coming years as research grows in this area. Below we provide some basic guidance for monitoring MP in soils based on the available literature.

2.4.3 Sampling

Although standardized sampling methods have yet to be developed for monitoring MP in soils, it is still important that reliable information on sample collection, processing, and plastic identification methodologies are provided to allow for comparison between sampling sites and to build the knowledge required to develop methodologies for monitoring programs. Box A outlines both the must have data for reporting MP concentrations in soils and the beneficial to have data.

Box A: Information needs for reporting microplastics in soils.

Must have data for reporting microplastics in soils

- Sampling location, including latitude and longitude
- Date including day, month, and year
- Description of ground cover including estimates of percent vegetation cover and vegetation type
- Description of soil type preferably using a formal soil classification system
- Sampling method (e.g., soil corer, shovel)
- Surface area sampled
- Depth of soil sampled
- Wet weight of sample
- Dry weight of sample
- Storage of sample (sample container) and conditions after sampling (e.g., stored in fridge)
- Method of organic matter removal
- Sieve size used for coarse and fine sieving
- Method of density separation
- Average number of MP particles (with standard deviation) determined through visual analysis reported in size categories 5 - ≥ 1 mm and 1000 - ≥ 300 µm
- For each plastic particle identify the category (e.g., fiber, film, foam, fragment), size class, shape, and color (reported in eight broad color groups)

Beneficial to have data for reporting microplastics in soils

- Soil organic matter content (determined though loss-on-ignition or similar)
- Particle size distribution of soils
- Polymer identification

2.4.4 Quality assurance/quality control (QA/QC) for microplastics in terrestrial soils

Providing recommendations on the quality assurance/quality control (QA/QC) protocols for monitoring MP in terrestrial soils is limited by the lack of research in this area, however, it is prudent to follow key QA/QC procedures from MP sampling in other abiotic compartments. Key QA/QC procedures are the use of both field and laboratory blanks (controls) to estimate potential background contamination of MP when sampling in the field and processing samples in the laboratory. Furthermore, to reduce the potential for contamination, it is recommended that samples remain covered as much as possible in the field and laboratory, and work with samples in the laboratory takes place in a clean room or under a clean hood. Importantly, due to a lack of data on the concentration and variability of MP in soils in the Arctic, guidance on the sample size and number of replicates needed to provide a reliable estimate of plastic pollution cannot be made at this time. This is an important area in which further research is required.

2.4.5 Recommendations for monitoring microplastics in soils

Given the unknowns around standardized methodologies, MP concentrations, and variability in Arctic soils, it is difficult to make recommendations on establishing an effective monitoring program for MP in Arctic soils at this time (Table 2.8). There are opportunities to collect well-documented soil samples from existing (or future) MP monitoring sites, at minimal costs, which could help establish future recommendations for MP monitoring in Arctic soils. To date no research has been conducted on MP in Arctic soils, therefore there is ample opportunity for research to fill important knowledge gaps on the presence, transport, and fate of MP in Arctic soils, as well as what impact if any these MP are having on terrestrial ecosystems (Table 2.8).

Table 2.8 Summary of monitoring and research recommendations for soils.

	1st level (must do)	**2nd level (should do)**
Monitoring	None at this time	Establish soil monitoring locations in regions where other contaminants monitoring is taking place ($)
Research	Study the concentration and variability of MP in Arctic soils ($) Examine the possible vertical transport of MP through the soil column and how permafrost alters this relationship ($$) Research how vegetation cover alters MP concentration in soils ($$) Transfer of MP from soils to aquatic environments through erosion and permafrost melt ($$$) Study potential degradation of MP in soils ($$$)	Impacts of MP on Arctic soil fauna ($$$) Impact of MP on Arctic vegetation ($$$) Impact of MP on Arctic soil processes and geochemistry ($$$)

2.4.6 Conclusions

Microplastics in soils is an under-researched area, particularly in the Arctic where no research yet exists. Nevertheless, soils are a critical component of Arctic ecosystems and one that is rapidly changing in the face of climate change. Furthermore, soils are a large abiotic compartment in the Arctic and if we want to understand the cycling of plastic contamination in the north, it is important to monitor this component. Research in this area is developing rapidly and it is likely that sufficient evidence will be available shortly to make more robust recommendations on potential monitoring programs.

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2.5 Ice and snow (from lakes and rivers, glacier cores, sea ice)

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2.5.1 Introduction

Both sea ice and snow in the Arctic are highly polluted with microplastics (MP; Obbard et al., 2014; Peeken et al., 2018a; Bergmann et al., 2019; Kanhai et al., 2020; von Friesen et al., 2020). Sea ice sequesters MP from the atmosphere (Bergmann et al., 2019; Allen et al., 2020) and from the underlying seawater and acts as a temporary sink and transport vehicle of MP pollution (Peeken et al., 2018a, Kanhai et al., 2020). Given the marked reduction in age, thickness, and extent of the Arctic sea-ice cover in recent decades (Polyakov et al., 2012; Stroeve et al., 2012), it is likely that this sequestered MP will be increasingly released into the pelagic Arctic and sub-Arctic systems.

2.5.2 Status of global science

Although MP have reached both polar regions (Isobe et al., 2017; Waller et al., 2017; Peeken et al., 2018b; PAME, 2019), so far, detailed studies of MP have mainly been reported for Arctic sea ice and snow (Obbard et al., 2014; Peeken et al., 2018a; Bergmann et al., 2019; Kanhai et al., 2020; von Friesen et al., 2020). Currently nothing is known about the plastic pollution of other components of the cryosphere, for example, Arctic lakes or glaciers (PAME, 2019). However, it is known that MP deposited in alpine glaciers have concentrations comparable to those found in European marine and coastal sediments (Ambrosini et al., 2019) and thus it can be anticipated they might also be found in Arctic glaciers. A high atmospheric input for Arctic sea ice was also claimed by Geilfus et al. (2019), who did find, near their university campus, through an open sea-ice tank experiment, high concentrations of MP in the top layer of the ice. However, in situ sea-ice cores taken from the Baltic Sea using the same method did not corroborate these results. This is in line with observations of Arctic sea-ice cores lacking high concentrations of MP at the surface (Peeken et al., 2018a; Kanhai et al., 2020). However, Bergmann et al. (2019) did find comparable high concentrations of MP in Arctic snow, but with a very patchy distribution. In general, it seems to be difficult to assess the role of snow in the deposition of plastic on sea ice because the history of the lain snow is difficult to identify. Another source for MP accumulation on sea ice might be sea spray, which has recently been reported to have high concentrations of MP (Allen et al., 2020) and might be a not yet accounted for source of MP in sea ice.

A recent study by von Friesen et al., 2020 further showed higher concentrations of anthropogenic microparticles close to wastewater outlets and in the marginal sea-ice zone. Currently, over four million people live in the Arctic (Heleniak and Bogoyavlensky, 2014) and most have no proper waste management or wastewater treatment. Thus, plastic debris from openly exposed waste disposal sites and MP from treated and untreated wastewater enter the marine environment continuously (Magnusson et al., 2016; Gomiero, 2019; Granberg et al., 2019) and could be a local source for sea-ice contamination. Other local MP pollution sources in the Arctic are related to shipping, fisheries, and tourism, particularly cruise ships (PAME, 2019). Typical polymers from activities like varnishing, e.g., polyamide and polyethylene, were traced as very small MP in Arctic sea ice (Peeken et al., 2018a).

In the Arctic, particular riverine input of MP might be an important source, but has so far not been investigated (PAME, 2019). Large fractions of Arctic sea ice grow on the shallow shelves, where riverine tracers are incorporated into the sea ice (e.g., Laukert et al., 2017), and potential MP with riverine origin can easily be transported far from their sources even in the Fram Strait (Peeken et al., 2018a; Teckmann et al., 2020). Given 11 % of the global riverine discharge enters the Arctic Ocean (Fichot et al., 2013), Russian and Canadian rivers are likely to constitute important local pathways for sources of MP to the Arctic Ocean and the sea ice.

Microplastics are also transported to the Arctic by air and ocean currents from distant sources (Lusher et al., 2015; Bergmann et al., 2019). Peeken et al., 2018a showed that various ocean currents have a unique MP composition imprint and the drifting sea ice thus is a local temporal sink and a redistributor of MP in the Central Arctic. Once they enter the major outflow gateways of the Arctic, MP are likely released in the marginal ice zone (MIZ; Obbard et al., 2014; Peeken et al., 2018a; von Friesen et al., 2020). Deposition of MP from the MIZ into deep-sea sediments was proposed by Bergmann et al., 2017 at the northern HAUSGARTEN site in the Fram Strait, which was further corroborated by a study from Teckmann et al., 2020 modeling the pathways of MP in the water column found in the Fram Strait. However, the ultimate fate of MP released from sea ice at the MIZ has not been investigated.

2.5.3 Trends to date

Microplastics compete with sea-ice algae when colonizing the sea ice (Hoffmann et al., 2020). Thus, it is important to understand the role of MP in sea ice; however, more studies are needed to describe trends in MP pollution. The four previous studies on Arctic sea ice show differences regarding the contamination concentrations (Obbard et al., 2014; Peeken et al., 2018a; Kanhai et al., 2020; von Friesen et al., 2020), however they are not comparable because of the different methods used and sizes reported. Methodology also differs between the investigations, which affects the final data obtained. When focusing only on numbers of particles, the concentration of MP would have increased dramatically between cores taken around 2005 (Obbard et al., 2014) and 10 years later (Peeken et al., 2018a). However, a new study focusing again on visible particles showed similarly low numbers, more comparable to the first study (Obbard et al., 2014; Kanhai et al., 2020). Most particles found in the Peeken et al., 2018a study, using µFTIR, were particles below 50 µm, which are overlooked with the visible observations, and explains the main differences between the studies (for detailed method comparison see Section 4.3).

To date, there are no pan-Arctic observations of MP in sea ice that would allow researchers to distinguish between the Atlantic and the Pacific inflow into the Arctic. Most sea ice of the European Arctic margin is influenced by drift ice formed on the Siberian shelves via the Transpolar Drift (Serreze et al., 1989), which is due to the offshore winds producing large polynyas, considered the main ice factory in the Arctic (Reimnitz et al., 1994). During its growth, the ice incorporates particles from the underlying water. However, currently there are no real studies on multiyear sea ice, which might have gone through several thawing/freezing life cycles. The interpretation of MP entrapment during these different life stages might get difficult and would require more research.

2.5.4 Benefits

The main benefit to studying first and second year sea ice is that it could easily be incorporated into ongoing sea-ice research programs, which would only require that more ice cores be drilled for the MP analysis. Because the particles are trapped in the sea-ice matrix, all precautions to avoid any contamination can be done in a specially equipped laboratory prior to analyzing the samples. Thus, no special training for people working in the field is needed. The study of sea ice provides important advantages in assessing global warming and Arctic ecological sustainability associated with MP because it will shed some light on pollutants associated with the MP (e.g., chemical additives) that might accumulate on the surface of the Arctic Ocean. It would further allow the study of feedback mechanisms, e.g., due to enhanced melting caused by the increase of black tire-originating MPs and could help to understand the role of MP in biogeochemical cycles of the Arctic Ocean.

Another benefit to studying sea ice would be the accumulation of MP particles in the sea ice compared to oceanic water samples. By applying the backtracking approach of the sampled sea ice, the general origin and drift path of the sea ice can be retraced (Krumpen et al., 2016), thus allowing the distinction of various sources for the contamination. Even ice-core samples that were taken proximal to each other can have a different sea-ice origin. By combining the backtracking with 1-D sea-ice growth models, it is possible to elucidate the source region of the sampled ice and also the location at which different types of polymers were imbedded into the sea ice (Pfirman et al., 2004; Peeken et al., 2018a).

2.5.5 Limitations

It is currently unknown how representative the sampling of individual cores is for an entire floe or region. Particularly in regions where the ice is quite dynamic, it can be extremely difficult to achieve a proper sampling site. Because pack ice is a moving target, year-to-year changes might be an effect of various sea-ice origins rather than changes in MP pollution. In addition, the season of sampled ice has a large influence on the sampling because in the summer, the ice floes are subject to deformation that is more dynamic across a given sampling area, whereas a denser ice cover in the spring reduces this impact (Renner et al., 2014). Thus, land-fast ice might be a more reliable environment to monitor MP accumulation. However, given the backtracking approach, by regularly monitoring pack ice we could gather data to distinguish the impact of release of MP at outflow gateways of the Arctic from other sources, and thus elucidate general pathways of MP entry and release in the Arctic (Peeken et al., 2018a).

So far, only four studies on Arctic sea-ice research have been carried out and thus, we are still lacking the measures on how to properly treat samples in the field and in the laboratory.

Unlike ice, snow cannot be tracked back to an individual ice floe and thus any MP contamination of snow should be studied with wet deposition samplers at locations where all other variables for atmospheric input are also monitored. Deformed snow in its compressed form, which is found on glaciers, would not be an ideal monitoring subject, but could be used for the assessment of the temporal impact of MP on various remote areas and could further improve the estimates of atmospheric input. However, glacier sampling would also involve another set of methods to accurately estimate accumulation rates of the snow, which can vary a lot from year to year (Hodgkins et al., 2005).

Through their often-massive watersheds and the variation in their annual release to marine waters, rivers play a crucial role in the overall freshwater budget of the Arctic. For parts of the year, the rivers are frozen, which would allow for some regular sampling during the winter period. However, it is yet to be determined whether large volume pump samples or frozen samples would produce the best samples to monitor this environment.

In summary, little information is available for the Arctic cryosphere and thus current recommendations will change as the field progresses.

2.5.6 Methods

Sampling of Arctic sea-ice cores

Sampling is preferably carried out annually in the spring in the sub-Arctic and lower Arctic regions and in the summer in the higher Arctic, when remote areas are more accessible. Sampling should be performed using traditional coring techniques, such as Kovacs 9 cm diameter corer (Kovacs, Enterprise, Roseburg, USA) used by, e.g., Obbard et al., 2014 and Peeken et al., 2018a. The snow should be removed before drilling the sea-ice cores. To prevent contamination with fibers from gloves, it is recommended to use colored Nitrile gloves during drilling. To make the process feasible for non- MP experts, one way to store the samples is in plastic bags (e.g., polyethylene tube films (LDPE) by Rische and Herfurth). Metal containers are also appropriate; and all cores should be stored at -20 °C prior to analysis. If possible, replicates should be taken, and monitoring programs particularly interested in mass (weight)-based budget of MPs in sea ice might want to collect a large number of ice cores to account for the more randomly distributed large particles. Additional ice cores from the same ice sheet should be collected to determine the biogeochemistry and history of the sampled sea ice.

Microplastics sample preparation

To prevent contamination of samples, handling and processing the sea-ice cores should be conducted under a clean bench or in a clean room. To exclude sample contamination from field sampling, transport, and storage, the surface of the ice core's outer layer should be removed prior to sectioning the core. Depending on the monitoring purpose, entire cores or individual sections should be melted in glass jars prior to filtration. The sectioning of the cores prior to melting is dependent on the results provided by the auxiliary parameters. Usually, the bottom section could be 5 cm and other sectioning should not go below 20 cm when using a standard Kovacs 9 cm diameter corer. The melted sea ice should be filtered and subjected to MP investigations. Currently, no standard methods are agreed upon and further details for visual inspection followed by FTIR can be found in Kanhai et al., 2020, whereas the details for µFTIR analyses, including very small particles (< 50 µm), are given in Peeken et al., 2018a. Given the high concentrations of very small particles in sea ice, studies of very small MP particles or even nanoplastic particles are highly recommended to study plastic contamination in this biome.

Blank test

So far, no standard applications for MP measurements in sea-ice cores have been established, therefore, best practices of other matrices should be applied. This involves a blank in the field (e.g., by placing open Petri dishes with wet tissues in the area of the coring site), blank samples during sample preparation in the laboratory, and blank samples of the storage bags. Once the community has agreed upon standards, this document can be updated.

2.5.7 Plastic identification

Given the high number of small particles in sea ice, observations with µFTIR microscopes (imaging FTIR) should be the preferred identification method of MP in sea ice. Other identification methods involve Raman microscope (imaging Raman) or thermal degradation methods (pyr-GC/MS). Details about the quantification and identification within each method are given in Section 4.3.

2.5.8 Existing monitoring for populations/contaminants in the Arctic

As of today, there are no official monitoring sites of sea ice (PAME, 2019). Monitoring could be implemented at the various pan-Arctic research stations (Figure 2.3) by collecting extra cores for MP. Current regular sea-ice sampling occurs in the Hudson Bay, near Cambridge Bay, and in Northern Baffin Bay. Another targeted area could be NE Greenland in the outflow of sea ice from the Arctic Ocean. At Young Sound (Daneborg/Zackenberg stations 74º N), it is possible to collect drifting sea ice during the summer months. The ice outside the fjord represents a mixture of ice exported from the Arctic Ocean. In addition, regular sampling campaigns like the ones occurring in Fram Strait (FRAM pollution observatory) could monitor the outflow of Arctic sea ice. Also, selected fjords on Svalbard or reoccurring Central Arctic cruises done by several nations could include additional sea-ice core sampling for MP.

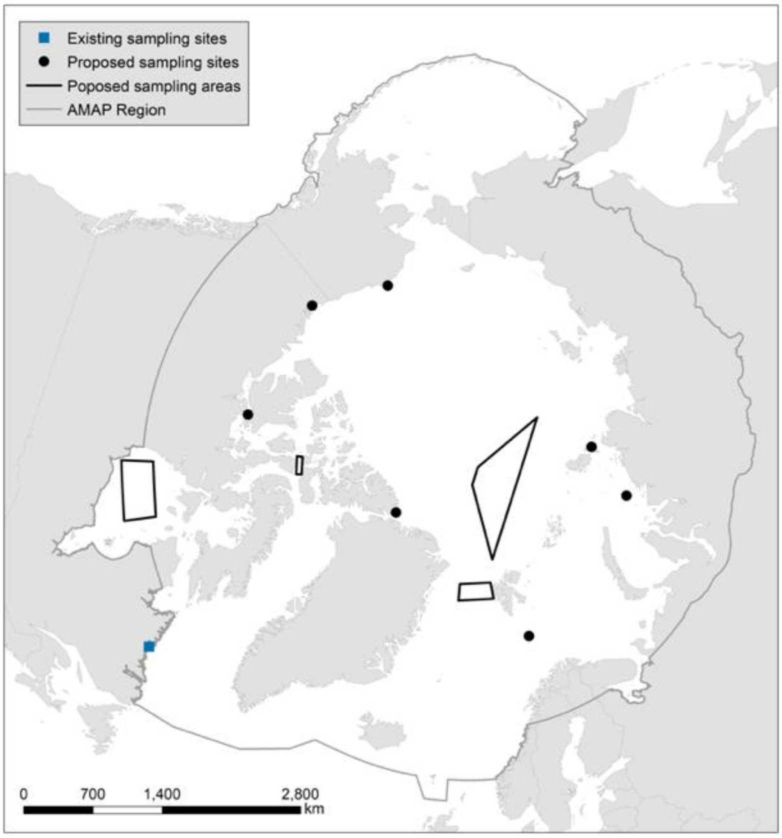

Figure 2.3 Map of potential monitoring sites for sea-ice coring at existing research stations or recurring research campaigns.

2.5.9 Suggestions for future activities/knowledge gaps

Microplastic pollution of sea-ice cores is still in the exploration phase and therefore it is recommended that regular sea-ice sampling be accompanied by additional MP sampling. This should involve sea-ice cores with several replicates per station at the main inflow and outflow gateways of the Arctic as well as on major drift paths, such as the Transpolar Drift or the Beaufort Gyre. In addition, land-fast ice areas, e.g., Alert or sites in Greenland, could be target areas to increase future monitoring sites. Land-fast ice will be of particular value to monitor local contamination sources.

Given that only four studies for MP in Arctic sea ice exist, it can be anticipated that the one-year sampling of sea ice, under ice water, and sea-ice fauna during the international one-year drift study, MOSAIC, will improve our understanding of plastic pollution in sea ice and the adjacent habitats. This unique data set might also give new insights about the value of monitoring sea ice in the Arctic.

Table 2.9 Summary of monitoring and research recommendations for sea-ice cores.

	1st level (must do)	**2nd level (should do)**
Monitoring	-	Use opportunistic sites to collect sea-ice cores for MP **Must have data** - Location - Date - Collection method - Temperature and salinity of cores - Ancillary biological data, such as biomass - Sea-ice type and section along the ice core - Polymer types and concentrations, sizes, and shapes **Nice to have for all data** - Backtracking of sea-ice cores - Polymer weight - Particle color - 1-D model of polymer types
Research	Study under ice water together with sea-ice cores Perform experiments to understand entrainment of MP particles into sea ice Study impact on sea-ice biota	Improve the understanding of sea ice as a sink and transport vehicle for MP pollution in the Arctic

Table 2.10 Summary rationale for recommendations, including estimated costs for implementing programs: 0 - already in place, $ - relatively inexpensive because of synergy with other projects but needs to have some additional capacity; $$ - either networks and capacity will need to be developed; $$$ - development of sampling networks, processing capacity, and reporting all need to be developed.

Recommendation	**Program Cost**	**Rationale**
Sea ice analyzed for MP particles mainly < 300 µm - Useful for monitoring, in alignment with atmospheric input - Understand the role of sources and sinks	$$	Monitoring programs currently not in place for sea-ice cores, but regular sampling of sea ice could include sampling for MP. The main cost involves processing and analyses of samples, which can be quite costly thus two-dollar signs

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Glacier face Croker Bay, Nunavut, Canada

2.6 Litter on Arctic and sub-Arctic shorelines

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2.6.1 Introduction

Monitoring of marine macrolitter, often also called marine debris, on shorelines is a widely used environmental indicator. It provides data for spatial and temporal assessments, such as amounts, composition, and pathways. Potentially, monitoring can also provide data on the risk of harmful effects of litter mainly in marine environments, and likely it could also be applied to larger freshwater systems. This information can also be used to identify important litter sources and thereby relevant actions for effective mitigating measures and to evaluate the effectiveness of existing legislation and regulations.

Litter is defined as any persistent, manufactured, or processed solid material directly or indirectly, intentionally or unintentionally, discarded, disposed of, abandoned, or lost in the marine and coastal environments. This also includes marine litter entering the marine environment via rivers, sewage outlets, storm-water outlets, or winds (OSPAR, 2010; Opfer et al., 2012). Macrolitter surveys on shorelines are looking for items larger than 2.5 cm. However, some types of smaller mesoplastic particles within the size range of 5-25 mm, such as industrial pellets, different specific small items, as well as fragments, can in some cases also be registered during surveys, although not always in the same quantitative manner. Microplastics (MP) can also be monitored on shorelines but see Section 2.3 for a more detailed description of those methods.

The shoreline is the interface between land and sea and is an important compartment for monitoring (GESAMP, 2019), because it is:

(i) where marine litter is often present in larger quantities;
(ii) often closer to land-based sources; and,
(iii) most accessible.

As a result, shorelines are typically the first environmental compartment considered for quantifying marine litter.

2.6.2 Status of global science

Many countries across different continents have implemented monitoring programs for marine litter on shorelines. Coordination of these programs occurs at different organizational levels through frameworks such as the European Marine Strategy Framework Directive, the US NOAA Marine Debris Program, and by regional sea conventions. The Group of Experts on Scientific Aspects of Marine Environmental Protection has also published suggested guidelines for the monitoring and assessment of plastic litter and MP in the ocean (GESAMP, 2019). In addition, efforts are ongoing to harmonize surveys and obtain data on marine litter pollution that are comparable at larger scales. This implies that the larger frameworks for monitoring marine litter on shorelines are relatively standardized, but that some national and regional variation in protocols exist. These shoreline monitoring activities, relevant at both spatial and temporal scales, are necessary to assess if there are changes in conditions that need to be addressed through management or policy. This could, for instance, involve implementation or adjustments to local, national, or regional action plans to reduce plastic pollution.

In different parts of the Arctic, some knowledge of amounts, distribution, composition, and sources of marine litter on shorelines already exists, but this knowledge is relatively fragmented and to a large extent based on non-coordinated efforts. The information gathered comes from surveys carried out by researchers, environmental institutions, or dedicated citizen science communities according to various standardized monitoring protocols, from assessments of litter items collected by volunteers, or from coastal clean-up campaigns. Using existing monitoring frameworks will be advantageous for time series consistency and data comparability, however, these same existing frameworks can also be challenging to further harmonization and more detailed comparisons because of data generated with different monitoring methods.

2.6.3 Trends to date

The experience and results collected from Arctic activities on marine litter assessments are reviewed in the recent desktop study by PAME, 2019. The study concludes that the availability of data still represents an insufficiency in numbers, timeline, geographical coverage, and comparability of surveys to determine trends in amounts, distribution, and composition of shoreline litter in Arctic areas. Being able to assess trends for marine litter on Arctic shorelines requires the establishment of a more coordinated monitoring effort, which should comprise more comparable standardized surveys carried out throughout the Arctic as performed within other Regional Seas Conventions, e.g., OSPAR and HELCOM.

2.6.4 Pros and cons of monitoring

Benefits

Litter on shorelines can give a good indication of sources, origins, and pathways of plastics and other types of litter in the environment because identification of (macro) litter items larger than 2.5 cm is relatively easy compared to, e.g., analyzing micro- and mesolitter particles. However, some identifiable items with sizes below 2.5 cm like cigarette butts and small lids can still be recorded according to protocols. In addition, shorelines are present in all geographic areas, and data can be collected with relatively both time-efficient and cost-effective efforts. Hence, surveys do not require expensive laboratory equipment and can also be performed by non-academic personnel following basic instructions and quality assessment/quality control (QA/QC) procedures.

Limitations

Arctic shorelines are often located in remote areas that are difficult to access because of infrastructure and the rugged nature of the landscape. In some regions, beach-like shorelines do not exist, but instead the shorelines are comprised of rocks and pebbles. Morphology of shorelines can therefore vary and affect surveys. Moreover, the shorelines can be covered by ice and snow during long periods of the year, thus preventing survey activities.

Different monitoring protocols are currently applied (e.g., OSPAR and NOAA MDMAP protocol), which can be challenging or can require additional effort when combining data for circumpolar assessments. In addition, not all Arctic relevant litter items may currently be included in the existing items lists.

2.6.5 Methods

Monitoring strategy

The Arctic area is characterized by a low population density, a less developed infrastructure, and harsh climatic conditions. These special conditions call for particular attention in the design and establishment of shoreline marine litter monitoring programs for the Arctic. Some shoreline litter surveys have been conducted in different Arctic regions using the internationally recommended OSPAR (OSPAR, 2010) or NOAA (Opfer et al., 2012) protocols, although often with some modifications. In the NOAA guidelines, only data generated for the "accumulation studies," in which all litter items on the full shoreline segment are removed, generate data similar to data generated using the OSPAR guidelines. The "standing-stock studies" in the NOAA guidelines provide data for marine litter left on the shoreline and not collected. This type of survey poses challenges for a wider pan-Arctic survey strategy because it would complicate data comparisons. These different monitoring strategies are also outlined in GESAMP, 2019.

Advantages and limitations for the adaptation of predetermined criteria in the OSPAR and NOAA monitoring guidelines, along with other relevant criteria, are considered with regard to implementation in an Arctic monitoring strategy (Table 2.11). These include:

- the shoreline typography and location of the shoreline (e.g., urban/populated vs. reference/remote),
- survey frequencies and the importance of continuity in monitoring surveys on selected shorelines,
- the expertise of the monitoring personnel,
- categories used for the registration of the different predefined litter items,
- units for reporting data, and
- the quality assurance of the surveys.

These criteria can be important for data comparison in wider regional assessments of shoreline litter in the Arctic.

In addition, it is important that a full survey unit of the shoreline, preferably 100 m, is surveyed, i.e., from the water's edge to the back of the beach, as defined by physical structures such as a transition zone to dunes, vegetation, rocks, etc., so that litter accumulated during more extreme weather events are recorded. For continuous monitoring efforts, GPS reference points must be used to ensure that exactly the same survey site is monitored during each survey.

Table 2.11 Summary of monitoring strategy with regard to recommended criteria for selection and conduction of marine litter surveys on Arctic shorelines.

Coastal morphology	Beach-like shoreline with sand, gravel, pebbles, or stones of different sizes, but not shorelines with cliffs. Preferably with clear depositional wash-up lines from both normal tidal conditions as well as more extreme weather conditions.
Length of survey segment	100 m defined by start and end GPS positions, but shorter segments as low as 50 m can be accepted, if limited by rocky shores.
Type of shorelines	Reference shorelines located in remote areas, preferably at an outer coastline (not inner fjords) and pointing toward the open sea. Locally impacted shorelines, e.g., from urban activities.
Definition of survey area	From the waterline to the back of the beach including the zone deposited during high-water levels caused by stormier conditions. Slippery areas due to settlement of, e.g., bladderwrack on stones below the normal waterline in the tidal zone can be excluded because of unsafe conditions for litter collection. A consistent and well-defined survey area of the shoreline should be identified for temporal monitoring.
Accessibility and survey frequency	The coastline should be accessible from land or by a boat. At least 1-2 seasonal surveys can be performed per year per location, i.e., summer (May-July) and/or autumn (August-October).
Collection and registration of litter items	All man-made litter items sized > 2.5 cm should be collected and identified according to types of litter described in either the NOAA or OSPAR guidelines.
Removal of litter items	Should be accessible for ease of marine litter removal. Larger litter items might be moved inland away from the shoreline, if team is not able to transport these items to an appropriate waste disposal site, so the items are not registered again during the next survey. Items too large to move should be marked on site in a way that they won't be registered again.

Selection of survey locations

The first criterium for the selection of a survey location is the coastal morphology. Beach-like shorelines, to a large extent, receive marine litter and other debris washed ashore from the sea and are easier and safer to thoroughly examine than rocky shores. However, in many parts of the Arctic, the shorelines will be dominated by rocks and cliffs, and beach-like coastal segments dominated by pebbles or different-sized stones will only occur in smaller, bay-like environments. The occurrence of sandy beaches, which are often preferred for international beach litter monitoring programs, are scarcer in the Arctic, although in some areas they do occur, e.g., in Alaska. In addition, these beach-like segments are often limited by rocky shores and therefore not always a full 100 m in length. Therefore, shorter shoreline segments should be accepted for Arctic monitoring even though a 100 m segment is the recommend length in the OSPAR and NOAA guidelines. Data then have to be normalized to 100 m before data generated for different shoreline lengths can be compared.

The second criterium is the selection of a survey location based on the expected relative impact from different litter sources. The location can be chosen because the shoreline predominantly receives litter washed ashore from the open sea (reference shoreline), or because the shoreline is impacted by contributions from local sources. Hence, the amounts and composition of marine litter can depend on both the geographical location relative to marine and land-based activities occurring in close proximity and the dominant hydrological conditions and wind regimes that will transport litter from the sea. This implies that the selection of the survey locations can be determinative for the marine litter data that are collected. In the design of a monitoring program for shoreline marine litter, the type of information preferred or required from the effort should therefore be considered.

An appropriate reference shoreline is ideally located in a remote area with no visible human activity nearby, preferably on an outer coastline (not inner fjords), and pointing toward the open sea, thereby mainly reflecting the pressures from long-range transport, sea-based-activities, and a more diffuse distribution of litter from land-based local sources. These characteristics allow for a reference value of litter deposition that does not receive an over-representative amount of litter from local or distance sources.

In contrast to this, the selection of so-called urban beaches located in the vicinity of towns and smaller settlements, including harbors, sewage effluents, and open dump sites, will reflect the impact of local litter sources. The ability and precision in the identification of either local or regional/international sources of litter to the marine environment can thus be influenced from the types and locations of beaches included in the monitoring program. Identification of litter sources is a prerequisite for implementation of targeted actions toward the reduction of these. Determination of the efficiency of the actions also requires measures of the amounts of litter released from the source or trends of the amounts and composition observed in the marine environment.

The third criterium is that the shoreline be accessible from land or by a boat, so it can be revisited for future surveys on a yearly basis.

Definition of survey area

A clear definition of the survey area and the units used for registration of the shoreline litter are essential to make the data comparable. The survey area preferably should be 100 m sections parallel to the waterline (see monitoring type, below), but an adaption to Arctic conditions should include lengths of less than 100 m based on accessibility. The width of the monitoring area is from the water's edge to the back of the beach/shoreline, characterized by the first presence of dunes, rocks, or a vegetation line. For Arctic beaches, a clear shift in the primary substrate or the presence of a barrier is often less visible. Therefore, the width could be the part of the beach directly affected by marine water fluctuations including the zone deposited under high-water levels and high winds. Slippery areas can be excluded because of unsafe conditions for litter collection.

Frequency of monitoring surveys

In the Arctic, climatic conditions shorten the feasible period for beach litter monitoring. Hence, during winter and spring, access to the beaches, particularly the reference beaches, can be very difficult or even impossible. Furthermore, ice and snow cover can disable monitoring. These challenges may limit the annual monitoring frequency.

The feasible number of surveys under Arctic conditions may only be one to two surveys per beach per year. This is lower than in the OSPAR guidelines, in which four monitoring surveys per beach are recommended (winter, spring, summer, and autumn) or the NOAA protocol in which monthly surveys are recommended. Allowing fewer monitoring surveys per year will affect the confidence in deriving baseline levels and assessing trends for the Arctic. For instance, it has recently been recommended for EU Marine Strategy Framework Directive (MSFD)-oriented assessments that national and subregional baseline levels be based on median-values of data from a minimum of 40 monitoring surveys within a 6-year monitoring period because this constitutes an optimum point for achieving a reasonable confidence interval width (van Loon et al., 2020). The median assessment value is robust against extreme values, which frequently occur in shoreline litter monitoring. Further analyses are therefore needed to assess the implications of fewer available AMAP-relevant survey data on the statistical power of trend analyses. This should be considered when designing monitoring strategies for litter on shorelines in Arctic and sub-Arctic regions.

Litter registration

For shoreline litter surveys in the Arctic, recording of litter items has predominantly been performed according to the OSPAR guidelines (e.g., data from Norway, Greenland, and Iceland) and the NOAA guidelines (e.g., data from Alaska and Canada). These two guidelines provide different litter item lists. The NOAA guidelines include descriptions of 44 different litter types divided into 6 material categories, whereas the OSPAR list from 2010 includes descriptions of 111 different litter types divided into 12 material categories. In addition, since 2018, OSPAR has started to extend the item list, which will be integrated into the Joint List of Litter Categories for Marine Macrolitter Monitoring prepared for shoreline litter monitoring under the MSFD in Europe (Fleet et al., 2021).

Subsequently, the description of litter items in the OSPAR and NOAA guidelines do not match and used separately, the two guidelines will generate different information on the composition of different types of litter items including, e.g., generation of top 10 list of the most often registered litter items. Therefore, if wider Arctic assessments want to include and compare marine litter data generated with both guidelines, some level of aggregation of litter types is needed to generate a more comparable dataset. Table 2.12 shows a proposal for how such an aggregation of litter items could be done.

Table 2.12 Proposal for aggregation of litter types described in the NOAA and OSPAR guidelines to prepare a more comparable dataset.

Aggregated name for litter types	NOAA litter types	OSPAR litter types	NOAA + OSPAR codes	OSPAR material category	NOAA material category
plastic/polystyrene pieces (> 2.5 cm)	N1a, 1b, 1c – plastic fragments (hard, foamed, film)	45 - foam sponge 46 - plastic/polystyrene pieces 2.5-50 cm 47 - plastic/polystyrene > 50 cm	N1a, N1b, N1c, 45, 46, 47	plastic	plastic
drinks (bottles, containers, and drums)	N3 – beverage bottles	4 - drinks (bottles, containers, and drums)	N3, 4	plastic	plastic
food package and assorted jugs and containers	N2 - food wrappers, N4 - other jugs or containers	5 - cleaner (bottles, containers, and drums) 6 - food containers incl. fast food containers 8 - engine oil containers and drums < 50 cm 9 - engine oil containers and drums > 50 cm 10 - jerry cans (square plastic container with handle) 11 - injection gun containers 12 - other bottles, containers, and drums 13 - crates 34 - fish boxes 38 – buckets 19 - crisps/sweet packets and lolly sticks	N2, N4, 5, 6, 8, 9, 10. 11, 12, 13, 19, 34, 38, 27	plastic	plastic
		27 - octopus pots	?	plastic	plastic
caps/lids	N5 - bottle or container caps	15 - caps/lids	N5, 15	plastic	plastic
cigarettes and buds	N7 - cigarettes	64 - cigarette buds	N7, 64	paper/cardboard	plastic
cigarette lighters	N8 - disposable cigarette lighters	16 - cigarette lighters	N8, 16	plastic	plastic
4/6 pack yokes	N9 - 6-pack rings	1 - 4/6-pack yokes	N9, 1	plastic	plastic
bags	N10 – bags	2 - bags (e.g., shopping) 3 - small plastic bags, e.g., freezer bags 112 - plastic bag ends 121 - bagged dog feces 23 - fertilizer/animal feed bags	N10, 2, 3, 112, (23)	plastic	plastic
rope, string, small nets (incl. pieces)	N11 - plastic rope/small net pieces	31 - rope (diameter > 1 cm) 32 - string and cord (diameter < 1 cm) 115 - nets and pieces of net < 50 cm 116 - nets and pieces of net > 50 cm 33 - tangles nets/cord/rope and string 28 - oyster nets or mussel bags incl. plastic stoppers	N11, 31, 32, 115, 116, 33, 28	plastic	plastic
floats/buoys	N12 - buoys and floats	37 - floats/buoys	N12, 37	plastic	plastic
fishing lures and lines	N13 - fishing lures and lines	35 - fishing lines (angling)	N13, 35	plastic	plastic

Aggregated name for litter types	NOAA litter types	OSPAR litter types	NOAA + OSPAR codes	OSPAR material category	NOAA material category
cups	N14 - cups (incl. polystyrene/foamed plastic)	21 - cups	N14, 21	plastic	plastic
cutlery/trays/straws	N15 - plastic utensils N16 – straws	22 - cutlery/trays/straws	N15, N16, 22	plastic	plastic
balloons, incl. plastic valves, ribbons, string	N17 – balloons	49 - balloons, incl. plastic valves, ribbons, strings, etc.	N17, 49	rubber	plastic
personal care products	N18 - personal care products	98 - cotton bud sticks	N18, 98, 99, 100, 18, 7	sanitary waste	plastic
		99 - sanitary towels/panty liners/backing strips		sanitary waste	
		100 - tampons and tampon applicators		sanitary waste	
		7 - cosmetics (bottles and containers, e.g., sun lotion, shampoo, shower gel, deodorant)		plastic	
		18 - combs/hair brushes		plastic	
		97 – condoms		sanitary waste	
		102 - other sanitary items		sanitary waste	
		103 - medical container/tubes		medical waste	
		104 – syringes		medical waste	
		105 - other medical items		medical waste	
other plastics	N19 - other (plastic) N6 - cigar tips	48 - other plastic items 14 - car parts 17 - pens 20 - toys and party poppers 24 - mesh vegetable bags 26 - crab/lobster pots 114 - lobster and fish tags 29 - oyster trays (round from oyster cultures) 30 - plastic sheeting from mussel culture (Tahitians) 36 - light sticks (tubes with fluid) 39 - strapping bands 40 - industrial packaging, plastic sheeting 41 – fibre glass 42 - hard hats 43 - shotgun cartridges 44 - shoes/sandals 101 - toilet fresheners	N19, N6, 48, 14, 17, 20, 24, 26, 114, 29, 30, 36, 39, 40, 41, 42, 43, 44	plastic	plastic
aluminum/tin cans	N20 - aluminum/tin cans	78 - drink cans 82 - food cans	N20, 78, 83	metal	metal

Aggregated name for litter types	NOAA litter types	OSPAR litter types	NOAA + OSPAR codes	OSPAR material category	NOAA material category
aerosol/spray cans	N21 - aerosol cans	76 - aerosol/spray cans	N21, 76	metal	metal
other metal	N22 - metal fragments N23 - other (metal)	89 - other metal pieces > 50 cm 90 - other metal pieces < 50 cm 77 - bottle caps 120 - disposable BBQs 79 - electric appliances 80 - fishing weights 81 - foil wrappers 83 - industrial scrap 84 - oil drums 86 - paint tins 87 - lobster/crab pots and tops 88 - wire, wire mesh, barbed wire	N22, N23, 77, 120, 79, 80, 81, 83, 84, 86, 87, 88, 89, 90	metal	metal
	N24 - beverage bottles	91 – bottles		glass	glass
other glass	N25 - jars		N25, N26, N27, 93, 92		glass
	N26 - glass fragments				
	N27 - other (glass)	93 - other glass items		glass	
		92 - light bulbs/tubes		glass	
gloves	N29 - gloves (rubber)	25 - gloves (typical washing up gloves) 113 - gloves (industrial/professional gloves)	N29, 25, 113	plastic	rubber
tires and belts	N30 - tires	52 - tyres and belts	N30, 52	rubber	rubber
other rubber	N28 - flip flops (rubber)		N28, N31, N32, 53, 50	rubber	rubber
	N31 - rubber fragments				
	N32 - other (rubber)	53 - other rubber pieces			
		50 - boots			
cardboard cartons	N33 - cardboard cartons	118 - cartons, e.g., tetrapak (milk) 62 - cartons, e.g., tetrapak (other) 63 - cigarette packets	N33, 118. 62	paper/cardboard	processed lumber
other paper and cardboard	N34 - paper and cardboard	61 - cardboard 66 - newspapers and magazines 67 - other paper items 65 - cups	N34, 61, 66, 67, 65	paper/cardboard	processed lumber
paper bags	N35 - paper bags	60 - bags	N35, 60	paper/cardboard	processed lumber
processed wood	N36 - lumber/building materials N37 - other (wood)	69 - pallets 74 - other wood < 50 cm 75 - other wood > 50 cm 68 - corks	N36, N37, 68, 70, 71, 119, 72, 73, 69, 74, 75	wood (machined)	processed lumber

Aggregated name for litter types	NOAA litter types	OSPAR litter types	NOAA + OSPAR codes	OSPAR material category	NOAA material category
		70 - crates 71- crab/lobster pots 119 - fish boxes 72 - ice lolly sticks/chip forks 73 - paint brushes			
clothing and shoes	N38 - clothing and shoes N39 - gloves (non-rubber)	54 - clothing 57 - shoes	N38, 54, 57, N39	cloth	cloth/fabric
other textiles	N40 - towels/rags N43 - other (cloth/fabric) N41 - rope/net pieces (non-nylon) N42 - fabric pieces	55 - furnishing 59 - other textiles 56 - sacking	N40, N43, N41, N42, 59, 56	cloth	cloth/fabric

* OSPAR litter items within the material category pottery and ceramics are not included in the table above because matching litter items do not occur in the NOAA item list.

In addition to the proposed list of aggregated litter items useful for pan-Arctic assessments (Table 2.12), it may also be worthwhile to add some other more specific litter items that are relevant to the Arctic because of local uses or frequency of occurrence in the Arctic. These may also be more relevant for a future regional action plan to combat marine litter in the Arctic. These items could be included as subgroups of existing litter types in the OSPAR and NOAA lists. Table 2.13 presents a list with examples of some potentially Arctic-related litter items.

Table 2.13 Some examples of marine litter items with higher Arctic relevance because of local uses and sources. If included, separate reporting codes need to be defined. The list can be modified or expanded over time based on inputs, e.g., from the process of developing the Arctic Regional Action Plan (RAP).

Description	NOAA code or subgroup of this	OSPAR code or subgroup of this	Material category
Melted plastic pieces, e.g., from outdoor incinerations	N1a	46, 47, 117	Plastic
Detonating cords for explosives, incl. fragmented pieces	N1a	46	Plastic
Aquaculture and animal feed bags	N10	23	Plastic
Plastic sanitary bags	N10	102	Plastic
Trawl net incl. pieces	N11	115, 116	Plastic
Gill nets incl. pieces	N11	115, 116	Plastic
Shotgun cartridges	N19	43	Plastic
Riffle cartridges for holding bullets	N19	(43)	Plastic

With regard to source characterizations, in addition to grouping the items according to the material categories, the litter types can potentially also be grouped according to their sources and uses. For instance, OSPAR, 2010 has proposed a division of the litter items into the following source categories:

- Fishery and aquaculture,
- Galley waste,
- Shipping and operational waste,
- Sanitary waste,
- Public littering (e.g., tourism),
- Not source characterized.

The assignment of shoreline litter items to different source categories can also be refined with detailed knowledge of local source patterns and pathways, e.g., by a Matrix Scoring Technique based on the likelihood that the litter items recorded originated from specific types of characterized sources (Tudor and Williams, 2004; Schäfer et al., 2019).

Further developments in methods to perform source characterizations from shoreline litter data are currently being assessed in different national and international frameworks. For instance, for the European MSFD, a new framework with a Joint List of Litter Categories for Marine Macrolitter Monitoring has recently been developed (Fleet et al., 2021), which provides a more detailed identification of litter items and subsequently is better to address most of the relevant litter items targeted in, e.g., the OSPAR regional action plan for marine litter, the European single-use plastic directive, or the US state and regional action plans for marine litter.

Unit for litter registration

The general unit for reporting data should be the number of litter items recorded per survey, ideally in a 100 m survey unit. For further comparison of data between different survey locations, data should be normalized to the number of items per 100 m shoreline segments.

As a supplement, the weight of each material category and the total weight of all collected items per 100 m can be recorded.

Monitoring personnel

Preferably, trained personnel should conduct surveys at specifically selected shorelines, revisited with regular frequency. This setup ensures high-quality monitoring data and more easily enables the comparison of surveys and trend analyses. However, because access and surveying are difficult for Arctic reference shorelines, the establishment of cross-linking networks with personnel involved in other field activities in these remote areas may be valuable. The regularity of other field activities in specific remote areas may vary. This may therefore imply a trade-off between the total number of shoreline surveys and the consistency in the selected shorelines and monitoring personnel. Hence, should an Arctic monitoring program be based on trained personnel dedicated solely to this specific task? Or can the monitoring program also take advantage of potentially less experienced personnel enabling surveys to be performed at otherwise non-included shorelines?

Safety

It is advised that monitoring starts one hour after high tide to prevent surveyors being cut off by incoming tide. It is recommended that a minimum of two people work on remote shorelines. Dangerous or suspicious looking items, such as ammunition, chemicals, and medicine should not be removed. Instead, police or responsible authorities should be informed.

Additional survey types

As a supplement to basic NOAA and OSPAR adjusted monitoring described above, other survey types can be relevant for studying amounts and composition of litter on shorelines, and these can provide additional information on sources and trends. These survey types are, at the moment, either only applied on smaller geographical scales, need further research and development, or are too expensive to be implemented for monitoring on a wider scale.

Standing-stock monitoring

Standing-stock studies, as described in the NOAA Marine Debris Shoreline Survey Field Guide (Opfer et al., 2012), can be executed on shorelines. This type of survey provides information on the long-term balance between continuous inputs and removal of marine litter on the shorelines, which is important for understanding its overall impact. Litter must be registered within discrete transects at the shoreline site and not removed during standing-stock surveys. The surveys need to be repeated several times, e.g., once per week or month. This can support assessments of the total load of litter and can be used to determine the density (number of items per unit area) of debris present.

Data generation by citizen science and large-scale clean-ups

Citizen science activities, e.g., in relation to clean-ups, have a strong component of public engagement in the scientific and policy-making process and can act as an important removal action for combatting plastic pollution in the environment. Citizen science driven clean-up projects can also potentially generate bulk estimates of litter amounts or identify the most frequently found items, especially if the generated data are reported in a systematic way to a database, e.g., using mobile phone applications that can improve the output because they provide harmonized approaches and ready data frameworks. Thereby some citizen science projects can more easily produce quantitative data on litter (e.g., total litter items per unit area (m^{-2}) or per unit length (m^{-1}) of a shoreline transect). In these projects, professional scientists typically accompany the volunteer participants to ensure data quality and comparability (GESAMP, 2019), although it can be challenging to establish continuous monitoring efforts and quality assured data within such frameworks.

There are several examples of citizen science and clean-up activities in the Arctic that generate data for assessing amounts and composition of litter items on shorelines, e.g., in Norway (Bergman et al., 2017; Falk-Andersson et al., 2019), Canada (e.g., https://civiclaboratory.nl/2015/07/25/beach-clean-ups/), Alaska (Polasek et al., 2017), and Greenland (Syberg et al., 2021), and even in some cases temporal trends (Haarr et al., 2020). Potentially, this can also involve tourists from cruise ships visiting more remote areas in the Arctic.

For instance, the citizen science data collected in Norway, which also include many AMAP relevant locations, are of sufficient quality to identify the main sources of marine litter in Norway on a broad scale but do have some limitations (Falk-Andersson et al., 2019). Comparable assessments on the usefulness of citizen science generated data have also been performed in Europe by the European Environmental Agency, which hosts the database for the European Marine Litter Watch (https://www.eea.europa.eu/publications/marine-litter-watch). In Norway, the NGO Keep Norway Beautiful (https://holdnorgerent.no/ryddeportalen/) is currently coordinating and mapping clean-up activities in cooperation with other groups and a newly established center for Oil Spill Preparedness and Marine Environment (https://www.marintmiljo.no/en/marin-forsopling/). Keep Norway Beautiful is working on improved mapping of areas where beach clean-ups have been performed. The wide range of protocols and structures within citizen science efforts create uncertainty in how to integrate them with assessments based on monitoring. Can these types of citizen science generated data be regarded only as supplementary data, or can they be assessed to have the quality necessary to be used for wider circumpolar assessments? If citizen science efforts generate data that can be used in a comparative way with data from more systematic and continuous monitoring efforts for marine litter on shorelines (e.g., for identifying sources and/or wider spatial and temporal trend assessments in the Arctic), they could be of significant value.

An alternative survey based on more detailed, in-depth analyses (in some studies called deep dives) has been developed for analyzing large amounts of litter collected from, e.g., large-scale clean-ups. This method can be a way to more efficiently provide detailed insights on sources and origin of marine litter at local or even (sub)regional scales, because this type of study includes a more detailed focus on the origin of different types of litter, e.g., fishery-related items. In addition, the framework for this type of survey can act as a useful tool when communicating with specific groups of stakeholders by involving them more directly. Such in-depth studies of marine litter on shorelines have been performed in different areas of Northern Norway and Svalbard (Falk-Andersson et al., 2018; Falk-Andersson and Strietman, 2019) and have recently been expanded to Greenland and Iceland (W.J. Strietman, *personal communication*). However, these studies will require both the collection of significantly larger amounts of litter and a more detailed registration of several of the litter items during the monitoring surveys than currently described in the NOAA and OSPAR monitoring guidelines.

Large-scale aerial surveys

Aerial surveys using drones or small manned aircrafts can be very helpful for carrying out rapid assessments of the distribution of litter over larger geographical scales by relying on the analyses of photo images, e.g., following major natural events, such as storms and tsunamis, or following accidents at sea (GESAMP, 2019). Aerial surveys also have the potential to identify coastlines that are sensitive as accumulation zones with high densities of accumulated plastic and other litter on the shorelines. This information can be used to optimize the efforts of clean-up actions (Deidun et al., 2019). Furthermore, aerial surveys can be particularly valuable for assessing marine litter in remote areas and could potentially be applied in monitoring programs. However, recognition of specific sizes of groups and types of marine litter will depend on image resolution, development of artificial machine learning algorithms for recognizing litter items, and amounts and types of other natural material on the shorelines that can interfere with identification (Deidun et al., 2019).

Modeling transport and identification of vulnerable coastlines

Hydrodynamic modeling can provide information on the importance of long-range transport with the North Atlantic or Pacific Ocean currents and can identify coastlines that are vulnerable to receiving larger amounts of litter from the open sea, both on larger and more local geographical scales. For instance, in Norway, oceanographic models for transport of floating litter and increased probability of stranding along the coast have been developed along the entire coastline (Huserbråten et al., *unpublished data*). The model will be validated with clean-up data from the NGO Hold Norge Rent (https://holdnorgerent.no/). Another Norwegian study has tested a GIS-based predictive model to identify marine litter hotspots in northern Norway that could predict a more effective site selection for maximizing removal of litter during organized coastal clean-up actions (Haarr et al., 2019).

2.6.6 Quality assurance/quality control (QA/QC)

Quality assurance

Hands-on training for fieldworkers is generally recommended for conducting reliable monitoring surveys on the shorelines, registration of the specific litter items according to the specifications in monitoring guidelines, and reporting the data to relevant databases. Trained and experienced surveyors can be researchers or long-term, community-led programs that perform coordinated monitoring continuously, or volunteers/citizen science doing single clean-ups. Detailed photo documentation of all collected litter for each survey can be useful for later confirmation. In many cases, photo documentation of every item may not be possible, in which case items that are difficult to categorize or specifically notable for low or high frequency should be the priority.

For the NOAA guidelines, there is an efficient setup for training surveyors with an online monitoring toolbox that includes tutorials, protocol quizzes, database user guides, etc. (https://marinedebris.noaa.gov/research/monitoring-toolbox).

Data management and reporting formats for databases

To perform thorough spatial and temporal trend analyses of the amount and composition of marine litter on Arctic shorelines, the availability of quality-assured monitoring data stored and secured in long-term databases is necessary. These databases are most useful when they are easily accessed, and the data they contain can be easily queried or exported in readily usable formats.

The OSPAR beach litter database (https://beachlitter.ospar.org) stores and secures marine litter data generated according to OSPAR beach-litter guidelines and collected at reference beaches in the Northeast Atlantic region, which includes some parts of the Arctic Sea. The reported data need to be normalized to 100 m beach segments. Currently, the database contains some AMAP relevant data from Arctic and sub-Arctic parts of Norway, Iceland, Faroe Islands, East Greenland, and West Greenland. However, OSPAR has recently indicated that they will consider not hosting data from locations outside the OSPAR maritime area, even though they are generated using comparable data formats. This may affect the long-term storage of the monitoring data from, e.g., West Greenland. Subsequently, the use of another database must be considered, even though a wider OSPAR database would be a better platform for the standardization and harmonization of monitoring efforts and data assessments in these neighboring regional seas.

Monitoring data generated according to the NOAA guidelines can be reported to NOAA's database under the Marine Debris Monitoring and Assessment Project (MDMAP): https://marinedebris.noaa.gov, which covers data from both maritime areas and greater lakes in the USA. An initial search shows data from 23 shoreline locations in Alaska, although only 2 of these are in the Arctic, for a total of 10 surveys in the Arctic.

The ICES DOME database can potentially also host these types of beach litter data based on EU TG-ML codes from JRC (2013) for specific types of litter.

In addition, for citizen science, including various types of clean-up events, data can be sent to and retrieved from a public dataset at the Marine Debris Tracker website (https://marinedebris.engr.uga.edu) or the Marine Litter Watch developed by the European Environmental Agency (https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-litterwatch#tab-news-and-articles). These listed platforms or apps are examples, and it is recognized that additional apps or platforms will be developed over time, although the specific connectivity challenges of the Arctic may continue to make them difficult to use there. New apps or platforms should be evaluated for potential utility as part of monitoring efforts on a case-by-case basis.

2.6.7. Existing monitoring for marine litter on Arctic shorelines

For some years now, several Arctic countries have initiated monitoring activities for marine litter on shorelines according to the recommended monitoring protocols. Table 2.14 lists the current availability of such monitoring data in the OSPAR and NOAA databases relevant for Arctic assessments.

Table 2.14 Summary table of the availability of monitoring data relevant for Arctic assessments in the OSPAR and NOAA databases (Status September 2019).

Country	No. of shoreline locations	Total number of surveys with monitoring data	Time period	Reference to monitoring guidelines	Availability of data in databases or from other data sources
Norway	5	42	2011-2019	OSPAR	OSPAR database
East Greenland	7	14	2016-2019	OSPAR	OSPAR database
West Greenland	10	46	2016-2019	OSPAR	(OSPAR database) [a]
Iceland	6	42	2016-2019	OSPAR	OSPAR database
Faroe Islands	1	4	2002-2006	OSPAR	OSPAR database
Alaska	2	10	2012+	NOAA	NOAA MDMAP database[b]

[a] The West Greenlandic data are currently stored in the OSPAR database, although they are from locations outside the OSPAR region.
[b] An initial search of the MDMAP database shows Alaska has 23 total sites, though only 2 of these are in the Arctic Ocean, with 10 total surveys in the Arctic.

In addition, Canadian data generated within the Nunatsiavut Government monitoring program (M. Liboiron, *personal communication*) can provide other relevant Arctic data that can be compared with the MDMAP and OSPAR data.

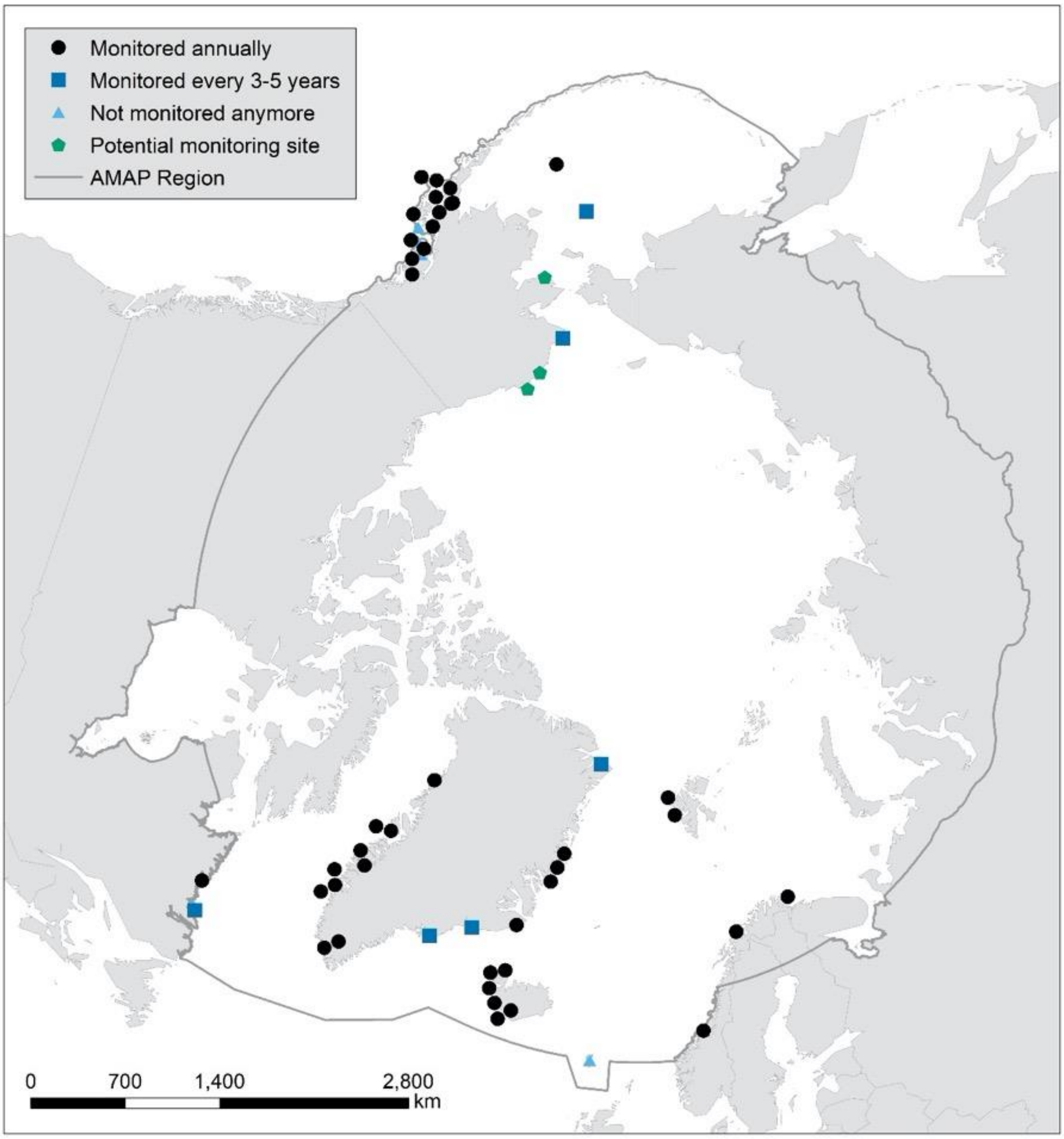

Figure 2.4 Map of locations for existing monitoring activities on marine litter on shorelines in the Arctic and sub-Arctic regions. In addition, Alaska has also indicated three sites as potential new monitoring sites. Overlapping points were offset to show all sampling locations.

2.6.8 Recommendations

Table 2.15 Summary of monitoring and research recommendations for macrolitter on Arctic shorelines.

	1st level (must do)	**2nd level (should do)**
Monitoring	Accumulation surveys of macrolitter at reference sites of 100 m segments on shorelines following OSPAR or NOAA guidelines.	Accumulation surveys of macrolitter at point source (e.g., urban) impacted shorelines for assessing inputs from local Arctic sources. Implementation of specific Arctic relevant litter items in an extended monitoring identification list. Standing-stock surveys according to NOAA protocols.
Research	In-depth analyses (deep dives) with more detailed source characterization of litter items.	Use of aerial surveys in monitoring programs for macrolitter. Fate of macrolitter on shorelines due to weathering processes and their potential as sources for MP. Hydrographic modeling, e.g., identification of coastal areas vulnerable for high accumulation of litter.

Table 2.16 Summary rationale for recommendations, including estimated costs for implementing programs: 0 - already in place; $ - relatively inexpensive because of synergy with other projects but needs to have some additional capacity; $$ - either networks and/or capacity will need to be developed; $$$ - development of sampling networks, processing capacity, and reporting all need to be developed.

Recommendation	Program Cost	Rationale
Accumulation surveys at 100 m segments on shorelines. Useful for monitoring in alignment with MDMAP, OSPAR, and EU MSFD, although would benefit from some minor adaptations to Arctic conditions.	0 - $	Existing monitoring programs are already in place in most OSPAR member states as well as in Alaska as part of MDMAP, although the number of monitoring stations could be increased. Other countries could also start up similar monitoring activities relatively easily. It will generally be low cost to implement such low-tech shoreline monitoring, i.e., conducting field surveys, characterizing litter items, and reporting the data, although ship-assisted transport will be needed for surveys in more remote areas.
In-depth analyses (deep dive) for more detailed source characterizations.	$-$$	Collection of large representative amounts of litter from shorelines will depend on local network and capacities. Registration of the many litter items can be quite time-consuming, although it can also be performed with local stakeholders and representatives from the civil society.

Box A: Data needs/expectations.

Must have data

- Station ID
- Location (defined by start and end GPS positions)
- Type of shoreline (reference shorelines in remote area, or locally impacted shorelines, e.g., from urban activities)
- Length of survey segment (m)
- Survey date
- Monitoring survey or a clean-up activity
- Protocol applied for identification and registration of litter items
- Counts for each type of registered litter item according to recommended protocols
- Responsible data rapporteur

Nice to have for all data

- Average width of shoreline segment
- Number of persons involved in surveys
- Shoreline topography and features (% sand, % pebbles, % rocks)
- Distance to nearest inhabited town/settlements and number of inhabitants
- Distance to nearest harbor
- Distance to nearest river mouth
- Reference to QA/QC procedures
- Total weight of sampled litter

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2.7 Seabed

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2.7.1 Introduction

The seabed accounts for 70% of the Earth's surface and is an important carbon sink. It has also been argued that the seabed acts as a final sink for marine litter, including microplastics (MP; Woodall et al., 2014). This section concerns macrolitter on the seabed. For recommendations regarding microlitter in sediments, please refer to Section 2.3. Plastic accounts for 62% of litter recorded on the seabed (https://litterbase.awi.de), which does not come as a surprise given that 50% of plastic from municipal waste has a density higher than seawater and sinks directly to the seabed (Engler, 2012). Over time, though, even lighter plastic sinks to the seabed due to biofouling and ballasting processes (Porter et al., 2018). Despite the importance of the seabed as a sink for litter, technical constraints have resulted in the seabed remaining one of the least explored habitats on Earth. As a consequence, little is also known about the scale and distribution of its pollution, especially in the Arctic region.

Although the deep seabed has long been pictured as a sparsely inhabited moonscape, research over the past decades has unveiled a biodiversity akin to that of tropical rainforests or coral reefs (Herring, 2002). However, little is known about the effects of plastic debris on these rich communities or biota. It has been suggested that items such as plastic bags smother and damage organisms from hard and soft substrata (Parker, 1990). Litter on the seabed can cause anoxia to the underlying sediment, which may alter biogeochemistry and benthic community structure (Green et al., 2015). Furthermore, litter may serve as substrate for the attachment of sessile biota in sedimentary environments and alter community structure and biodiversity (Schulz et al., 2010; Mordecai et al., 2011). In addition, litter could become entangled in emergent epifauna, leading to injury, breakage, mortality, and disease (Yoshikawa and Asoh, 2004; Chiappone et al., 2005). Debris from fisheries may continue to attract mobile biota leading to ghost fishing and increased mortality (Matsuoka et al., 2005). Plastic debris may also be ingested by benthic organisms, including demersal fish. To date, records of impacts on benthic life remain largely anecdotal.

2.7.2 Status of global science

Plastic on the seabed was first recorded in McMurdo Sound, Antarctica (Dayton and Robilliard, 1971) and Skagerrak in 1972 (Holmström, 1975), followed by the Mediterranean (e.g., Galil et al., 1995; Galgani et al., 1995a, 1996; Stefatos et al., 1999; Katsanevakis and Katsarou, 2004), other European coasts (Galgani et al., 1995a, b, 2000), the US (June, 1990; Moore and Allen, 2000; Keller et al., 2010; Morét-Ferguson et al., 2010; Watters et al., 2010; Schlining et al., 2013; Law et al., 2020), and other areas (Lee et al., 2006; Fischer et al., 2015; Shimanaga and Yanagi, 2016; Chiba et al., 2018). Litter was also recorded in the Arctic including Alaska and the Bering Sea (Jewett, 1976; Feder et al., 1978; June, 1990; Hess et al., 1999) and the deep seabed (Galgani and Lecornu, 2004; Pace et al., 2007; Keller et al., 2010; Mordecai et al., 2011; Wei et al., 2012; Pham et al., 2013; Ramirez-Llodra et al., 2013; Amon et al., 2020), including hadal trenches such as the Mariana Trench, the deepest part of our ocean (Peng et al., 2018). Litter densities on the seabed range between 30-6,610 items km^{-2} (Keller et al., 2010; Pham et al., 2014) and are strongly influenced by the distance to the coastline, regional population densities, proximity to shipping routes, rivers, depth, marine landscapes, sampling and analysis approaches, water currents, and circulations (Jambeck et al., 2015).

Marine litter is defined as any persistent, manufactured, or processed solid material discarded, disposed of, or abandoned in the marine environment (UNEP, 2009). Material densities, fouling processes, size, and shape are important for transport distance and sedimentation rate. Outside of the coastal regions, the highest densities of marine litter have been found in submarine canyons, whereas continental shelves and ocean ridges have the lowest densities (Galgani et al., 2000; Ramirez-Llodra et al., 2011; Pham et al., 2014; Woodall et al, 2015; Buhl-Mortensen and Buhl-Mortensen, 2017).

This suggests there are transport mechanisms for seabed litter to the lowest points in the world's oceans. In the Mediterranean, densities of marine litter collected by trawling from deep waters (mean depth 1,400 to 3,000 m) ranged from 400 kg km^{-2} at the continental slope south of Palma de Mallorca to densities between 70-180 kg km^{-2} at the other sites (Galgani et al., 2000; Pham et al., 2014).

Densities of litter in the Ryukyu Trench and in the basin of Okinawa in the Northwest Pacific ranged from 8-121 kg km^{-2}, whereas shallower continental slopes or abyssal plains ranged from 0.03-9 kg km^{-2} (Shimanaga and Yanagi, 2016). In the European part of the Atlantic Ocean, densities of 43-74 kg km^{-2} have been recorded in the Bay of Biscay (Lopez-Lopez et al., 2017), while a mean of 123 kg km^{-2} has been estimated for the Norwegian shelf and the slope of the Norwegian Sea, and a mean of 154 kg km^{-2} has been recorded offshore in the Barents Sea (Buhl-Mortensen and Buhl-Mortensen, 2017).

Higher levels were recorded from coastal areas: a mean of 2,510 kg km^{-2} was observed along the Norwegian coast from Ålesund to Lofoten and 227 kg km^{-2} from Lofoten to the Russian border (Buhl-Mortensen and Buhl-Mortensen, 2017). Fishery-related litter dominated. This consists of a combination of wire, nets, and ropes. By weight, metal (wires) dominated, whereas plastic (nets and ropes) often dominated by volume. This agrees with findings from other areas with high fishing activities, such as on oceanic ridges and seamounts (Pham et al., 2014; Woodall et al., 2015). The 62% global contribution of plastic to marine total litter includes 11% from fisheries.

2.7.3 Seabed mapping in the Arctic

Marine debris was reported from trawls conducted in sub-Arctic regions as early as 1975/1976 in the Bering Sea (Jewett, 1976; Feder et al., 1978). In June (1990), marine debris was also recorded, including plastic in trawls from this area. No data have been published to date on seabed litter from the central Arctic, Chukchi Sea, or Amerasian Arctic.

The ongoing Norwegian seabed mapping program Mareano (www.mareano.no) has conducted > 2,000 (~700 m long) video transects. Litter was recorded for all transects and > 1,200 have been conducted in the Barents Sea (Figure 2.5). Items larger than 5 cm are observed by video recordings. This dataset provides an overview of the distribution, density, and composition of litter in a wide area, covering depths from 50 to 2,700 m and includes a variety of marine landscapes (Buhl-Mortensen and Buhl-Mortensen 2017, 2018). The density of litter decreases toward the north and with distance from the coast. In the Barents Sea, the mean density near the coast and offshore is between 268 and 194 items km^{-2}, respectively. Litter is unevenly distributed in marine landscapes and the density of litter on the deep-sea plain, continental slope, and shelf is mainly below 200 items (160 kg)/km^{-2}. Fjords and canyons exhibit higher densities, indicating an accumulation effect in these areas. Mapping information from Mareano provides vital background information for a designated seabed litter monitoring plan.

Iceland is currently recording all bycatches of litter made as part of bottom trawl surveys. Seabed mapping using video has been conducted in several localities and observed litter items have been recorded since 2015. More than 1,000 annual stations of stock-assessment surveys are used to register and classify marine litter (Figure 2.6; Hafrannsóknastofnun/Marine and Freshwater Research Institute, Iceland, *unpublished data*).

In the Faroe Islands, litter is also recorded as part of an ongoing ground fish survey using bottom trawls. In 2017, seabed mapping using video was started as part of the NOVASARC project (https://novasarc.hafogvatn.is/) and 60 localities were targeted (Figure 2.7). In total, only 13 litter items were recorded, all of which were fishing lines (P. Steingrund, Faroe Marine Research Institute, *personal communication*).

2.7.4 Trends to date

Data from bottom trawls conducted as part of the Russian-Norwegian Ecosystem Survey between 2010-2016 showed widespread pollution in the Barents Sea region, with litter found in 34% of the samples, yielding on average 26 kg km^{-2} of marine litter. Plastic accounted for 11% of the debris by weight. The highest quantities were found in areas west, southeast, and northeast off Svalbard (Grøsvik et al., 2018). The number of litter recordings from both bottom stations increased in the period these recordings were conducted (2010-2018). Plastics dominated all types of litter in bottom trawl stations both during the 2010-2013 and 2014-2018 periods (ICES, 2019). For bottom trawls, 81.0% of litter recorded was plastic during the 2010-2013 period, whereas 88.7% of litter recorded contained plastic during 2014-2018. Litter from fisheries—ropes, strings, and cords, pieces of nets, floats/buoys, etc.—dominated recordings of plastic litter (ICES, 2019).

Plastic litter has also been sporadically recorded off the East Greenland slope (Schulz et al., 2010) and at the HAUSGARTEN observatory in the eastern Fram Strait, providing rare time-series data for litter, especially for litter on the seabed. Analyses of still imagery from repeated towed camera transects, conducted at three different stations located along a latitudinal gradient, indicate an increase in litter on the seabed from 2002-2017, with an initial strong increase in 2011, followed by elevated levels above 6,000 items km^{-2} from 2014 onward (Figure 2.7; Martínez et al., 2020). The northernmost station, which is situated close to the marginal ice zone, exhibited the highest amount of litter and experienced the strongest increase from 346-7,374 items km^{-2} between 2004 and 2017 (peak of 10,358 items km^{-2} in 2016), respectively. Interestingly, glass was the predominant material type at this location. This is important; it points to local ship-based disposal because glass sinks directly to the seabed due to the material's high specific density. However, the quantities of plastic also increased over time with highest levels at the central HAUSGARTEN station (~5,000 items km^{-2}). If all three stations and years are combined, plastic accounted for 41 % of the litter. The use of imagery also allowed a rare assessment of marine litter impacts on benthic biota. Most frequently litter was entangled in sponges (54%), followed by colonization of items by sea anemones (22%). There was an increase of litter entangled in sponges over time at the northern station, which affected 10% of the sponge population in 2015. At the northern station, up to 28% of the sponge *Cladorhiza gelida* was affected whereas at the southernmost station up to 31% of the species *Caulophacus arcticus* was entangled.

2.7.5 Benefits of monitoring

- Temporal and spatial changes
- Litter quantity and composition changes
- Basis for monitoring the impacts of introduced mitigation measures to reduce litter

Time-series observations on the seabed lend themselves particularly well to monitoring purposes because the seabed represents a sink that integrates changes over long time scales. In contrast, estimates from the sea surface can be considered snapshots in time, being much more affected by weather, windage, and mesoscale phenomena (van Sebille et al., 2020).

2.7.6 Limitations

As in other environmental studies, seabed litter assessment can be reported in a variety of dimensions, e.g., size, weight, numbers, categories, area. Bycatch litter from trawl surveys is often provided as weight, and the litter sampled by the trawl allows for further analysis. Visual seabed mapping, on the other hand, typically reports on number per area of different litter categories, and weight can only be estimated. Visual mapping, however, allows for observations of litter in vulnerable ecosystems, e.g., coral reefs, and provides detailed information on litter position in the marine landscape. Both methods come with their advantages and disadvantages, and data cannot be compared directly because of sampling efficiency and habitats covered. For monitoring purposes, it is recommended that seabed litter be documented both through sampling and visual recording, and data should be presented in as many dimensions as possible using standardized methods to allow for a broad international comparison of seabed litter densities and composition.

2.7.7 Methods

Methods for monitoring litter on seabed have recently been reviewed (Canals et al., 2021). For recording litter from seabed, we refer to the Guidance on Monitoring of Marine Litter in European Seas (MSFD Technical Subgroup on Marine Litter, 2013) and the updated list of litter categories as described by Fleet et al., 2021 and the online Photo Catalogue of the Joint List of Litter Categories.

Recordings in the HAUSGARTEN study were performed by using a camera platform (OFOS, Ocean Floor Observation System), which was towed at a target altitude of 1.5 m for 4 hours. Items of 1-2 cm can be recorded with this approach and smaller items are disregarded. In recent years, the system provides both video and still imagery, but only still images are used for image analyses giving rise to the HAUSGARTEN time series. The advantage of this system is that it does not damage the ecosystem under investigation, unlike trawls, which cause more harm killing all organisms inhabiting this sensitive region. In addition, much larger areas can be covered. In this area, trawls deployed for 30 minutes come up with large amounts of animals and mud, which takes hours to sort as previous biological work, focusing on benthic biota, has shown (Bergmann et al., 2009). Another important advantage of using cameras is that it shows litter items in situ such that interaction with biota can be analyzed. For example, with this approach, we were able to show that up to 28% of the sponge species *Cladorhiza gelida* suffered from entanglement at station N3 and up to 31% of the sponge *Caulophacus arcticus* sustained entanglement at station S3 in certain years (Martínez et al., 2020).

In addition, previous research has shown that deposition rates in this area are quite low (Müller et al., 2012), so that items only become buried into strata as deep as half a meter over centenary time scales.

Still, they can be covered in a thin veneer of sediment, obscuring their detection. Nevertheless, we consider this drawback minor compared to the benefits of covering a large area and obtaining in-situ glimpses of litter. In addition, it ties in with an ongoing biological long-term observation program, so no additional ship time is needed, regular access is granted, and additional biological data are available (e.g., species densities, which allows assessment of vulnerability, e.g., to litter entanglement).

2.7.8 Litter estimates based on imagery

Litter is recorded on an annual basis in the Fram Strait at five seabed stations at the HAUSGARTEN observatory using a towed camera system (OFOS) operated by the Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research (Figure 2.8). All stations are characterized by soft sediments, with occasional dropstones and depths ranging from 1,200-2,500 m (Meyer et al., 2013; Taylor et al., 2016). Additional transects are done occasionally in the Molloy Deep (5,500 m depth), the deepest known depression in the Arctic Ocean. The camera is towed along the same camera tracks at ~1.5 m altitude taking video and a still images every 30 seconds. All still images are uploaded and analyzed manually using the online image database and annotation tool BIIGLE (Martínez et al., 2020). The benefit of this work is that it is embedded in an ongoing time-series program and therefore requires no additional efforts in terms of logistics and ship time. It was this research that initially raised concerns about plastic pollution in the Arctic (Bergmann and Klages, 2012).

Working class ROVs have also been used for in-situ experiments and image transects at HAUSGARTEN. However, this has been done on an irregular basis only because ROV charters are costly and logistics are more challenging compared with towed camera platforms. Their usage may increase with the new RV Polarstern, which will come equipped with robotic capabilities. Other platforms for image acquisition are autonomously operated vehicles (AUV) equipped with a camera payload, as recently developed by the AWI. The advantage of using imagery is that it does not cause harm to the environment, shows litter in situ (such that interactions with benthic life can be observed), and it enables both large- and small-scale assessment distribution patterns. The disadvantage is that it does not produce physical samples that can be investigated in further detail regarding material type, age, or origin. Imagery also fails to show items buried in the upper sediment surface layers, and white objects can be challenging to discern (from shells) due to reflectance.

Trawls must be considered semi-quantitative (Eleftheriou and Moore, 2005) because they may not be in constant contact with the seabed and the retained catch depends on the catch composition and mesh size used. In addition, trawls disturb the ecosystem and cover smaller areas. However, trawl surveys generate physical samples for close inspection, e.g., according to OSPAR protocol and can be conducted with low logistic effort and cost if implemented as part of regular fisheries stock assessments.

2.7.9 Fishing for litter - abandoned, lost, or otherwise discarded fishing gear (ALDFG)

A pilot Fishing for Litter (FFL) action ran in the Faroe Islands during the spring of 2008. The scheme has recently been restarted with four trawlers participating. The portion of plastic/polystyrene constituted 95 % of the litter collected (https://fishingforlitter.org/faroe-islands/).

The Norwegian Environment Agency established a national FFL test scheme in 2016-2017, which began initially with three participating ports (http://fishingforlitter.org/norway/). This was quickly extended with an additional five ports during 2017. The FFL scheme was continued in 2018 and extended with one more port. By 2019, the FFL scheme comprised a total of nine participating ports along the Norwegian coast. The FFL scheme is administered by SALT Lofoten AS in collaboration with Nofir, the local ports, and waste management companies.

2.7.10 Quality assurance/quality control (QA/QC)

Data recording and management should be an online, national database system controlled by local managers. Regional/country coordinators would then review and approve uploaded data. This would ensure consistency within each region and create a hierarchy of quality assurance on data acquisition. For International Bottom Trawl Surveys (IBTS), sampling data are collected in the DATRAS database and participate in data quality checking for hydrographical and environmental conditions. This process may also support quality assurance for data on litter.

The online portal LITTERBASE (https://litterbase.awi.de) contains peer-reviewed data on marine litter from different ecosystem compartments. It could be beneficial to allow data connections between this and the new portal.

Box A: Data needs/expectation.

Must have data for reporting plastic

- Location, including latitude and longitude, depth
- Date, including day, month, and year
- Sample method (trawl type, mesh size, opening size, ROV, video, still camera, SCUBA diving surveys), speed, distance, altitude, sampled area, minimal size limit
- Hydrographical (CTD)
- If multiple counts (transects/observers) are run at any given site (replicates)
- Primarily number and if possible weight (volume) per km^{-2}
- Category, material, source

Beneficial to have

- Color reported in eight broad color groups as reported in Galgani et al. (2017)
- Polymer type and method used (all sizes?)
- Size of plastics reported by size classes (mega/macro/meso)
- Interactions with biota (by material type, size, species, type of interaction)

2.7.11 Existing monitoring for contaminants in the Arctic

The joint Norwegian-Russian Ecosystem Survey in the Barents Sea is performed annually in August-October and includes sampling of several fish species, shrimp, and sediments for contaminants monitoring. Floating debris and litter as bycatch in trawls are also recorded and reported. Microplastics are collected from manta trawls (mesh size 335 µm) from some of the stations (Figure 2.9). In addition to time series of litter on the seabed, the HAUSGARTEN observatory work also includes annual sampling of deep-sea sediments for MP analyses (Bergmann et al., 2017a; Tekman et al., 2020), as well as occasional surveys in the water column, sea ice, snow, (Bergmann et al., 2019; Tekman et al., 2020), and zooplankton, and macrolitter surveys at the sea surface and on the beaches of Svalbard (Bergmann et al., 2016, 2017b).

2.7.12 Recommendations

Research gaps

Although the European Arctic seems to be covered reasonably well, very little is known about macroplastic pollution in the Central Arctic Ocean and the North American Arctic in terms of seabed litter. Limited historical data on marine litter presence and composition exist, primarily from Bering Sea bottom trawl surveys. Image footage from previous AWI expeditions to the central Arctic in 2013 and 2016 (Boetius et al., 2013; Boetius and Purser, 2017) exists, but has not been analyzed in terms of litter quantities. The same applies to footage from the Canada Basin (Bluhm et al., 2005; MacDonald et al., 2010). Footage may also be available from previous dives of the Russian ROV *Mir*. Analysis of historic footage could be a good starting point to diminish our knowledge gaps regarding plastic pollution in remote Arctic regions, but such work likely requires additional financial support.

Table 2.17 Summary of monitoring and research recommendations for litter on the seabed.

	1st level (must do)	**2nd level (should do/develop)**
Monitoring	- Develop a monitoring plan for seabed litter (> 2 cm*) by selecting representative sites for visual inspection that will cover different depths and substratum in marine landscapes. - Record litter (> 2 cm*) collected or observed in all sampling of seabed habitats (bycatch from bottom surveys, diver observations, camera surveys, etc.). - Perform studies that give information on within gear uncertainty and between gear uncertainty.	- Develop more automated and autonomous ways to record litter on the seabed.
Research	- Improved optics/image recognition for litter observations.	

* Size ranges between < 2 cm are not properly covered by these methods.

Table 2.18 Summary rationale for recommendations, including estimated costs for implementing programs: 0 - litter and plastic pollution monitoring already in place with regular funding; $ - relatively inexpensive because new litter and MP monitoring programs can use existing programs to obtain samples in at least some regions, but need to have some additional capacity to process samples for litter and plastic pollution; $$ - either sampling networks and/or capacity need to be developed to monitor litter and MP pollution; $$$ - development of sampling networks, processing capacity of samples, and reporting all need to be developed in the majority of the Arctic regions.

Recommendation	Program Cost	Rationale
Recordings of bycatch of litter from ongoing ecosystem surveys.	$	Many stations, large area coverage.
Video recordings, repeated visit from selected area, e.g., HAUSGARTEN or Mareano	$$-$$$	HAUSGARTEN: monitoring in place, but extra cost for the analysis of samples/imagery needed.

Between 100-200 stations may be recommended to cover plains and landscapes in a representative way based on experiences from the Mareano mapping, although statistical analyses may be the best basis when planning the number of stations.

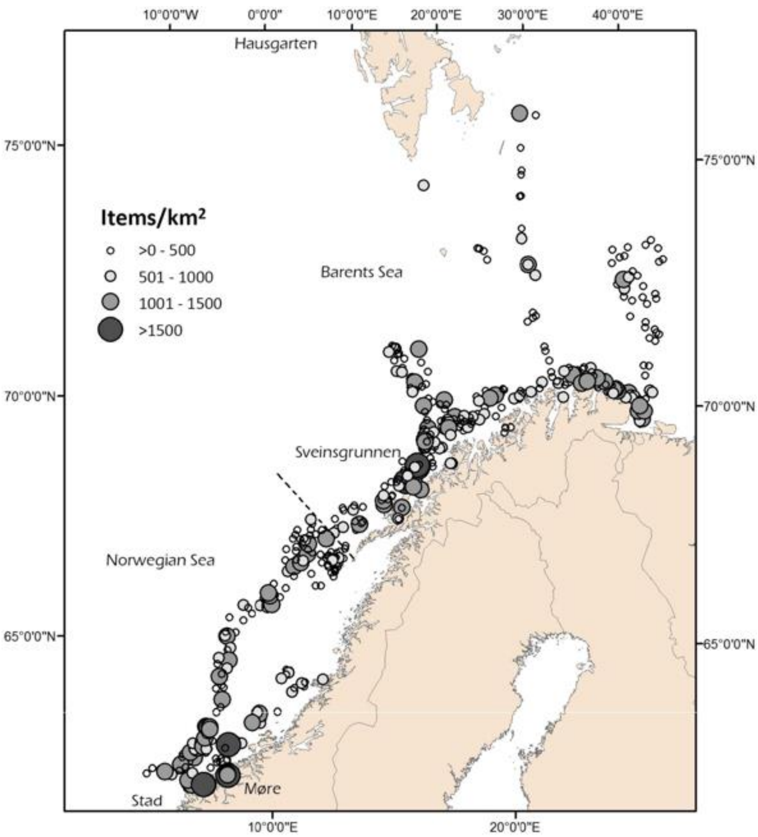

Figure 2.5 Litter densities (kg/km^{-2}) on 1778 video stations in Nordic Seas based on data from the Mareano program from 2006 to 2017. Dashed line marks the border between the Barents Sea and the Norwegian Sea (from Buhl-Mortensen and Buhl-Mortensen, 2017).

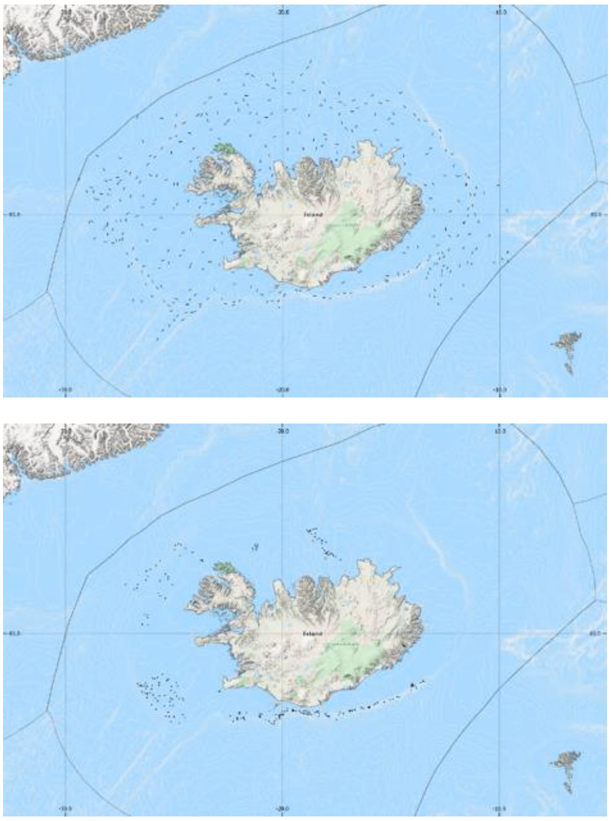

Figure 2.6 Iceland is recording litter both as part of the bottom trawling conducted and as part of the bottom fish surveys (upper map). In addition, litter is recorded as part of the ongoing visual mapping of the seafloor (lower map). Information is from Hafrannsóknastofnun/Marine and Freshwater Research Institute.

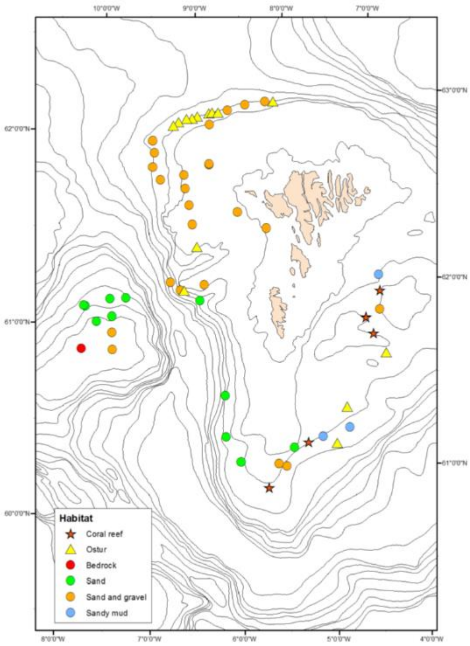

Figure 2.7 The position of 60 video stations where sediment, fauna, and litter were recorded in 2017 as part of the NOVASARC project. Information is from the Faroe Marine Research Institute.

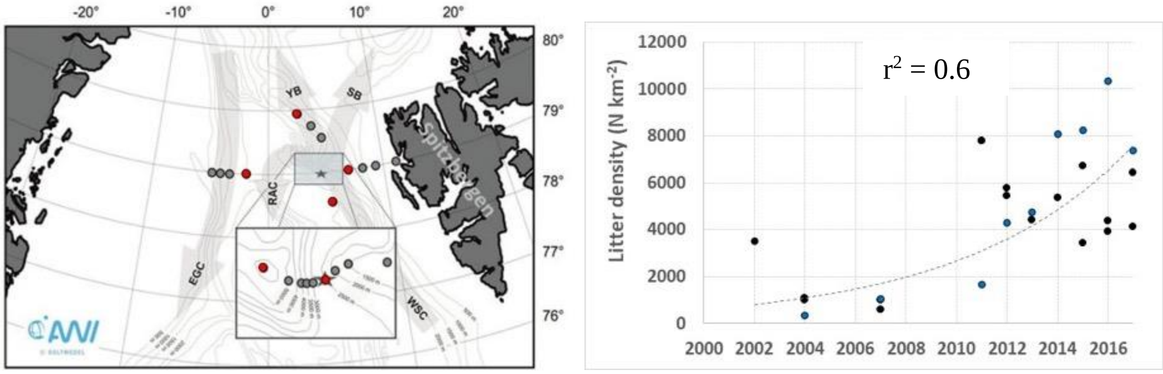

Figure 2.8 (Left) Location of sampling stations of HAUSGARTEN observatory run by AWI since 1999 in Fram Strait (red circles point to stations with camera surveys, ©T. Soltwedel). (Right) Litter densities recorded between 2002 and 2017 during camera transects undertaken at HAUSGARTEN, blue circles reflect measurements from the northern station (based on data from Martínez et al., 2020).

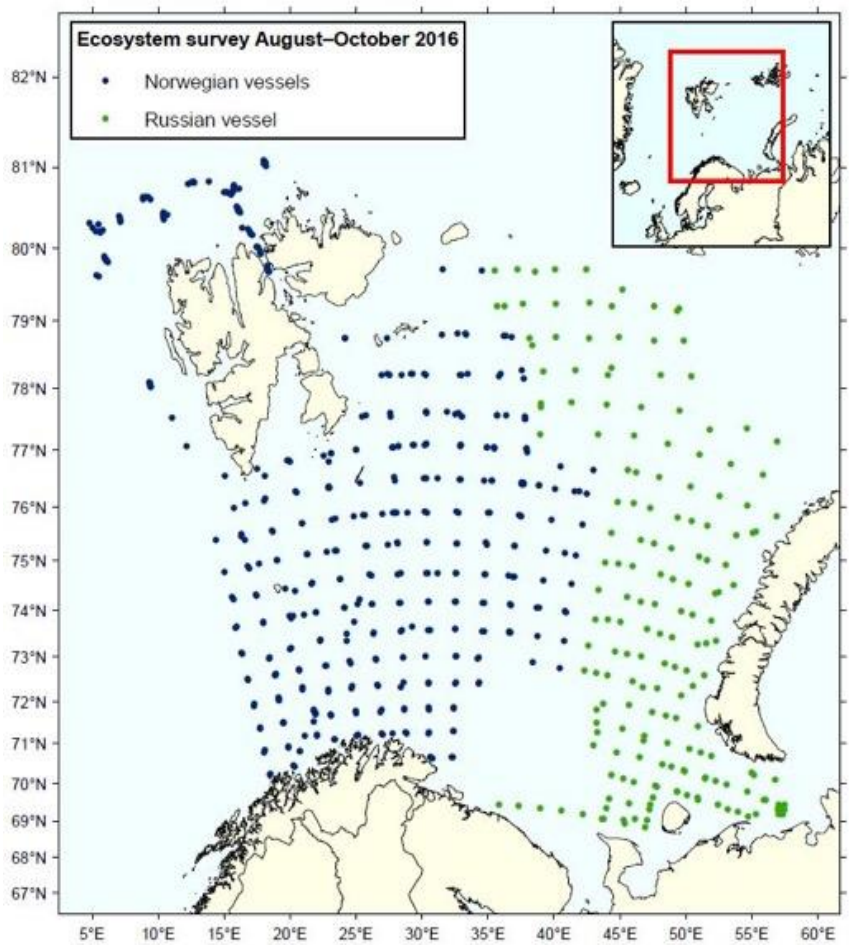

Figure 2.9 The joint Norwegian-Russian ecosystem survey in the Barents Sea performed annually in August-October include approx. 300 stations.

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3.0 Guidance for Monitoring Biotic Environmental Compartments

3.1 Invertebrates (benthic and pelagic)

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3.1.1 Introduction

Monitoring levels of microplastics (MP) particles in the sub-Arctic and Arctic marine food web can give us information on occurrences and abundances of MP pollution, as well as provide indications of ecosystem health. It is, however, important to recognize that invertebrate samples may not provide time trends or reflect environmental concentrations as clearly as some abiotic compartments due to biotic selection processes. There is also often great variation in MP counts between species and among individuals within the same site, something that hampers interpretation (Setälä et al., 2016; Gomiero et al., 2019; Piarulli et al., 2019; Bråte et al., 2020). Marine invertebrates, both pelagic and benthic, encounter a multitude of particles daily, provoking the development of strategies to reject particles of low nutritional value from actual food items. There is limited evidence that ingested MP are translocated through respiratory and intestinal epithelia and accumulated in tissues (Browne et al., 2008; von Moos et al., 2012; Avio et al., 2015; Brennecke et al., 2015; Welden and Cowie, 2016; Cui et al., 2017; Abbasi et al., 2018; Abidli et al., 2019; Mohsen et al., 2019). Many size ranges or types of particles are most likely ingested and egested. Exceptions exist related to, for example, the gut physiology of Norway lobsters (*Nephrops norvegicus*) where ingested fibers accumulate in the gut between molts (Welden and Cowie, 2016). An interesting effect was described in Antarctic krill (*Euphausia superba*) and Norway lobster showing that the gastric mill can break down MP to smaller sizes and translocate them to different anatomical compartments (Dawson, 2018; Cau et al., 2020; Martinelli et al., 2021).

Coupled with information on how different polymer types, shapes, and concentrations may affect selected species and life stages in controlled laboratory experiments, environmental concentrations may be used for risk assessments (Kögel et al., 2020). Many laboratory studies, however, use unrealistically high exposures (e.g., Cole et al., 2013, 2016; Setälä et al., 2014). This may reflect environmental MP concentrations when comparing extremes in MP exposure such as city harbors but not with remote offshore sites (e.g., Bråte et al., 2020). Furthermore, most studies expose with round plastic beads, not with fragments and fibers, which are prevalent in the environment. These studies function as “proof of concept” but have their limitations when deducing the fate and effects of MP in nature (Phuong et al., 2016). More information is therefore needed on which sizes, forms, and polymer types can pose problems for invertebrates under realistic exposure situations. Size matters more than shape (Lehtiniemi et al., 2018), and MP of larger size fractions will probably only provide a snapshot of MP ingestion at the time of sampling.

Updated ecotoxicological information will be key for accurate assessments of good environmental status and for informed advice to management on possible impacts and mitigation efforts. Recognizing these shortcomings, it is useful to establish indicator species for different parts of the food web, both from the water column and the benthic fauna, and species representative of Arctic ecosystems.

3.1.2 Summary of information to date

There have till now only been a handful of studies quantifying and characterizing ingestion of plastic pollution in marine invertebrates from the Arctic.

Pelagic invertebrates

Several studies have shown uptake of MP in zooplankton under natural conditions, for example in the Northwest Pacific and the coastal waters of Southeast Alaska and British Columbia (Desforges et al., 2015) and in salps from the North Pacific Subtropical Gyre, California Current (Brandon et al., 2019). Huntington et al., 2020 reported the presence of MP in various species of zooplankton from the Eastern Canadian Arctic. In the Huntington et al., 2020 study, MP were found in about 90% of zooplankton samples, and at a mean abundance of 0.7 ± 0.9 pieces per gram of zooplankton.

The ability of zooplankton to ingest MP has been demonstrated in several laboratory experiments (reviewed in Galloway et al., 2017 and Villarrubia-Gómez et al., 2018). Microplastic ingestion by zooplankton may have negative effects, as demonstrated in laboratory conditions when polystyrene particles in the size range 1.7-30.6 µm induced gut-blockage and increased gut-retention times leading to reduced feeding function (Cole et al., 2013), as well as reduced fecundity linked to the physical disturbance caused by the presence of plastic in the digestive tract (polystyrene particles, 20 µm; Cole et al., 2015). It should however be pointed out that the particle concentrations in these two studies were extremely high compared to what is normally found in the environment, $4x10^6$ MP L^{-1} and 75,000 MP L^{-1}, respectively. Water concentrations of MP > 11 µm in the area around the HAUSGARTEN observatory in the Arctic were found to range between 0 and 1.3 MP L^{-1} (Tekman et al., 2020).

The degree of transfer and bioaccumulation of plastic-associated toxic substances, such as persistent organic pollutants (POPs), to zooplankton and fishes is an active area of research, but evidence is currently limited (Lohmann, 2017). The amount of natural organic material to which POPs can adsorb outnumbers the amount of plastics and MP by many orders of magnitude. In a study from the South Atlantic Ocean by Rochman et al., 2014, several hydrophobic organic contaminants were analyzed in plastic debris and in mesopelagic lantern fishes, and the only correlation that might indicate an uptake in the animals from the plastic was found for polybrominated diphenyl ethers (PBDEs), used as flame retardants.

The melting zone of Arctic sea ice is an important part of the Arctic ecosystem with high productivity and biodiversity. Because the Arctic sea ice has been reported to contain high levels of MP particles (Obbard et al., 2014; Peeken et al., 2018; von Friesen et al., 2020), levels of MP particles taken up by ice-associated zooplankton would be interesting to monitor by sampling zooplankton living close to the melting zone, although sampling approaches may be challenging.

Benthic invertebrates

Microplastics sink to the seafloor due to the polymer having a density greater than seawater (Woodall et al., 2014; Kowalski et al., 2016; Erni-Cassola et al., 2019), by being weighed down by biofouling (Kaiser et al., 2017; Rummel et al., 2017), orby being incorporated into marine snow (Porter et al., 2018; Zhao et al., 2018). Because of this, benthic fauna feeding on settling particles or sediments constitutes a relevant matrix for monitoring MP pollution (GESAMP, 2019). Fang et al., 2018 reported MP in 11 species of benthic invertebrates (including starfish, shrimp, crab, whelk, and bivalves) sampled from the Bering and Chukchi Seas. They found averages of 0.02-0.46 pieces per gram wet weight or 0.04-1.67 pieces per individual. The greatest concentration appeared at the northernmost site in the Chukchi Sea, implying that the sea ice and the cold current represent possible transport media for MP ingested by benthic fauna and pointing to transfer mechanisms similar to those implied by the research carried out in the Fram Strait by Peeken et al., 2018. In many of these studies, microfibers were the most common MP form found.

Bivalves

Filter-feeding species like bivalves have been suggested as candidate organisms for monitoring the uptake and effects of MP particles in seawater and sediments (GESAMP, 2019). Bivalves are reported to be selective with regard to the uptake of MP and they egest particles as feces and pseudofeces, and therefore their suitability as an indicator species has been questioned (Ward et al., 2019).

Bråte et al., 2018 reported an overall average abundance of 1.5 MP per individual blue mussel (*Mytilus edulis*) sampled from Norwegian waters (n = 29 sites, 545 individuals). This study was extended to test the applicability of other benthic bivalves in Nordic waters. Interestingly, it was relatively hard to obtain high numbers of individuals in many of the site locations requiring the study of more than one closely related species. Five bivalve species, including mussels, from 100 sites were selected: 32 of the hard-bottom species *Mytilus* spp., 14 of the 3 soft-bottom species *Limecola balthica*, 31 *Abra nitida*, 20 *Thyasira* spp., and 3 of the hard-bottom Arctic *Hiatella artica*. Four of the five species were found to contain MP: *Mytilus* spp., *L. balthica*, *A. nitida*, and *Thyasira* spp. At 11 *Mytilus* sites, 2.77 or more MP per individual were found, with the inner Oslofjord mussels containing the highest concentration of MP (> 61 MP per individual), both in 2017 and 2018. Areas of Skagerrak, Kattegat, the Baltic Sea, and the North Sea close to urban areas were also found to have high levels of MP compared to other sites. Black rubbery particles were dominant in *Mytilus* spp., *A. nitida*, and *L. balthica*. These rubbery particles could stem from road runoff or other sources of rubber such as tires used in harbors. Microplastics between 63 and 1,000 µm were present in *A. nitida* and *L. balthica,* however, no MP larger than 63 µm were detected in *Thyasira* spp. This study shows that urbanized areas in the Nordic marine environment are receiving high levels of MP, and that bivalves could be used to monitor small MP. It also highlights that bivalves from the Nordic environment are exposed to rubber, and the sources of rubber should be further investigated.

Blue mussels collected in Iceland contained on average 1.3 MP particles per individual (Halldórsson and Guls, 2018). Blue mussels collected at different sites near Sisimiut in Greenland contained on average 6 ± 5 MP items per individual with greater concentrations closer to wastewater outlets and dumping sites (Granberg et al., 2020). Microplastic content was also analyzed in samples of the suspension feeding bivalve, Greenland smoothcockle (*Serripes groenlandicus*), collected in Kongsfjorden and Rijpfjorden, Svalbard. Of the individuals collected, 69% contained one or more MP with an average of 1.2 ± 1.1 particles per individual (von Friesen, 2018). These low counts obscured any differences between collection sites, which stresses the need for research regarding appropriate Arctic monitoring species.

Crustaceans

Approximately 20% of snow crabs (*Chionoecetes opilio*) in the Barents Sea contained MP in their stomachs (Sundet, 2014). Amphipods (*Gammarus setosus*) collected in the Kongsfjorden-Krossfjorden system, Svalbard, Norway, contained very few anthropogenic microparticles (2 ± 2) and no difference was detected among sampling sites, regardless of proximity to possible sources (Granberg et al., 2020).

Echinoderms

Deep-sea starfish (*Hymenaster pellucidus*) from Rockall, Great Britain, contained 1.6 MP per g ww (Courtene-Jones et al., 2017). Of the litter items observed on the seafloor of the HAUSGARTEN observatory, 67% were in some way interacting with epibenthic megafauna (Bergmann and Klages, 2012). We suggest future work focuses on these organisms to inform expected contamination in local food webs and to help us understand the fate of MP in Arctic food webs (e.g., trophic transfer, bioaccumulation, biomagnification, trophic dilution; Provencher et al., 2019).

3.1.3 Sampling

Sampling invertebrates in the environment should consider local conditions. For example, sampling mussels from suspended ropes/lines in the aquatic environment may result in higher levels of ingested MP based on the substrate. Therefore, the habitat of any benthic invertebrates should be considered. Often, 30 individuals are collected for monitoring surveys, but the number of individuals sampled should be planned according to requirements for statistical analyses. Directly after collection, invertebrates should be rinsed with seawater to remove debris, with filtered (0.2 µm) MQ water, and subsequently stored individually in aluminium foil covered and lidded pre-rinsed (three times with 0.2 µm filtered MQ water) glass jars. All samples should be stored frozen (-20 °C) and dark until MP extraction and analysis. Swift handling of individuals after collection prevents sample loss through organisms expelling material from their guts or ingesting plastics in another environment than their own. Open containers to control for air dust during sampling should be provided.

3.1.4. Extraction

Size and weight measurements and preparation of biota for extraction should take place in a clean air laminar flow cabinet to avoid airborne MP contamination. There are several tissue digestion protocols used for invertebrates, for example, a gentle and effective digestion protocol uses pancreatic enzymes from swine (von Friesen et al., 2019). Potassium hydroxide (KOH) is mostly used for bivalves (Bråte et al., 2018, 2020; Gomiero et al., 2019). General recommendation of protocols should await a process of international standardization and harmonization. The most important factor when selecting a digestion method is to control for and keep at a minimum MP degradation and loss, while removing enough of the tissue and other particles to enable analysis.

Box A: Data needs/expectations for reporting MP in invertebrates.

Must have

- Name of researcher
- Species
- Location, including latitude and longitude
- Date: day, month, year, time
- Sampling method (e.g., vertical plankton trawl 180 µm mesh size, diving, benthic trawl, cages/pots)
- Sampling depth (m)
- Size, weight
- Physiological status: relevant support data for the different species, e.g, season, sex, spawning status, molting stage, condition index
- Tissue(s) sampled
- Total number of samples/individuals per site (i.e., n)
- Filter type and pore size used
- Total and relative abundance of MP particles (with lower size limit)
- Particle category (e.g., fragment/foam/sheet/fiber/other), size, color reported in eight broad color groups, or mass per tissue weight and particle size group, as mean, with standard deviation and number of samples, median, and range for particles > 300 µm
- Collection, extraction, analysis method including equipment, quality assurance/quality control (QA/QC), limit of detection of MP size and/or mass, and measurement uncertainty

Beneficial to have for all data

- Polymer type (according to Figure 3 in Primpke et al., 2017)
- Either MP mass or number per tissue weight and particle size group, as mean, with standard
- deviation and number of samples, median, and range for particles < 300 µm

3.1.5 Quality assurance and quality control

In general, systems for QA/QCs need to be developed. Overall, QA/QC for any invertebrate studies should have sampling blanks and laboratory blanks to account for background contamination, especially of microfibers. See Section 2.2 for a more detailed description of laboratory blanks.

3.1.6 Recommendations

Given the lack of harmonized protocols for monitoring in many species and the wider diversity of species found across the pan-Arctic, the primary recommendation is to focus on suspension feeding species (e.g., mussels) that can contribute to the monitoring of MP in the environment, and in future studies, to examine the effects in relation to ecosystems and human health (Table 3.1).

Table 3.1 Summary of monitoring and research recommendations for litter and MP monitoring in Arctic invertebrates.

	1st level (must do)	**2nd level (should do/develop)**
Monitoring	Long-term monitoring on widely available species: • Suspension feeding bivalves, e.g., mussels (*Mytilus* sp.) or (*Serippes greenlandicus*) (*) MP cut-off size: 300 µm (visual determination, stereomicrosope, or chemical identification with FTIR)	Quantify particles < 300 µm in all invertebrates examined Develop knowledge to advise on other benthic or pelagic species with different feeding strategies like scavenger, deposit, or suspension feeder. Candidate species to consider: • Annelids • Sea cucumbers (*Holothuroidea*) • Calanus copepods (e.g., *C. glacialis* or *C. finmarchicus*) • Gammaridae (e.g., *Gammarus cetosus*) • Shrimp • Krill
Research	Recommendations for first prioritized tasks (short term): • Number of individuals needed • Statistical analyses/power analyses, modeling • Sessile versus motile • Functional groups • Location Investigate other pelagic or benthic species with regard to sampling and monitoring strategies, e.g.: • Ice associated zooplankton • *Pteropoda* pelagic snails (sea angels) • Larvacea (class *Appendicularia*) • Crabs (e.g., snow crab, *Chionoecetes opilio*)	

(*) We are aware of the challenges with bivalves egesting particles as feces and pseudofeces (Ward et al., 2019), although they seem less selective with fibers and other material types. We know less about the selectivity of other invertebrates. We suggest starting with MP > 300 µm for 1st level in the recommendations to comply with recommendations for other compartments. This size range could be used with bivalves but is more uncertain with other species. Recommended species at 1st level (must do) should be reevaluated when more data are available.

Table 3.2 Summary rationale for recommendations, including estimated costs for implementing programs: 0 - already in place; $ - relatively inexpensive because of synergy with other projects but needs to have some additional capacity; $$ - either networks and capacity will need to be developed; $$$ - development of sampling networks, processing capacity, and reporting all need to be developed.

Recommendation	Program Cost	Rationale
Community-based monitoring and collection of bivalves that are commonly consumed.	$	Many communities in the Arctic harvest bivalves regularly (e.g., mussels, clams). Community-based monitoring sampling programs should be developed to collect bivalves of interest for monitoring levels of ingested MP. This would also provide samples for effects from plastic contaminants for future studies.
Use existing Arctic cruises to obtain pelagic invertebrate samples.	$$	Existing monitoring programs are already in place for sediments regarding pollutants, trophic status, and biota making it easy to include sampling for MP. The main cost involves processing and analysis of samples, which can be quite costly, thus two dollar signs.

3.1.7 Existing monitoring for invertebrates/contaminants in the Arctic

The joint Norwegian-Russian ecosystem survey in the Barents Sea performed annually in August-October includes sampling of several fish species, shrimp, and sediments for contaminant monitoring. Floating debris and macrolitter as bycatch in trawls are recorded. Microplastics are collected from manta trawls from some of the stations. Organisms for MP monitoring can be provided upon request (Figure 3.1).

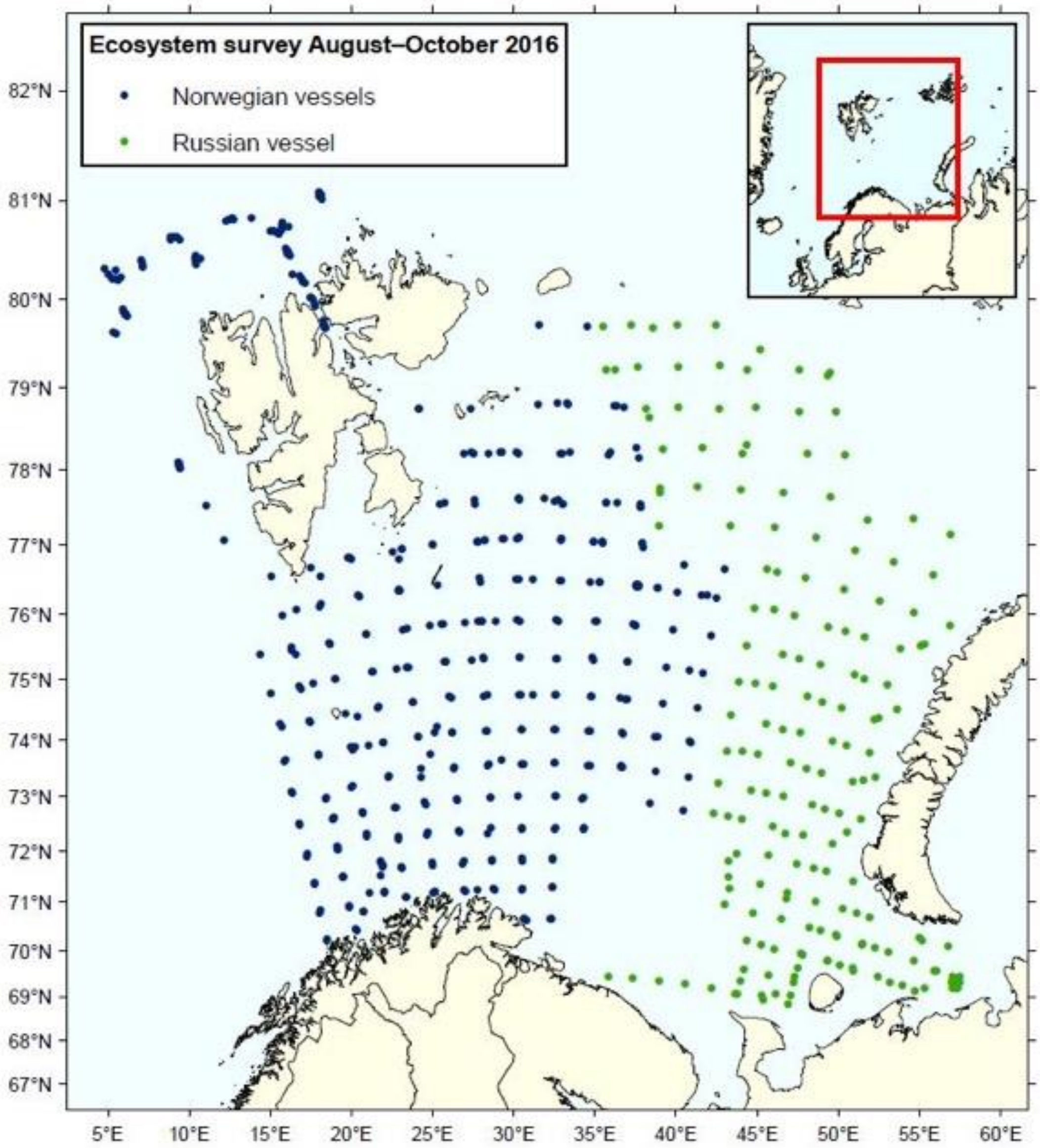

Figure 3.1 The joint Norwegian-Russian ecosystem survey in the Barents Sea performed annually in August-October includes approx. 300 stations.

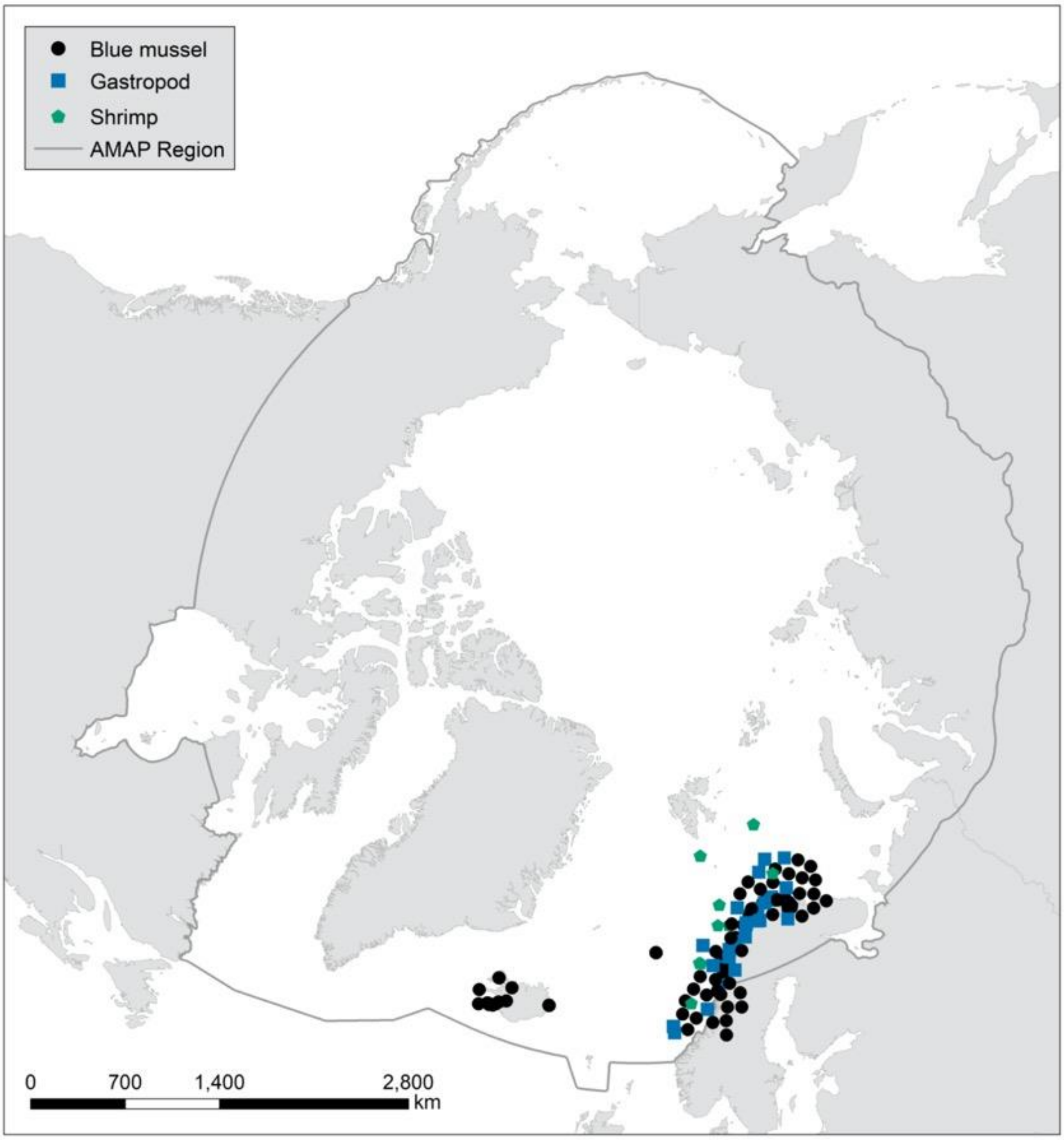

Figure 3.2 Locations of existing sampling for MP in invertebrates in the AMAP region.

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3.2 Fish

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3.2.1 Introduction to microplastics in Arctic fish

Plastic pollution of the ocean has led to ubiquitous but uneven exposure of organisms, including fish, to microplastics (MP). Evidence of plastic pollution in the Arctic (Lusher et al., 2015; Buhl-Mortensen and Buhl-Mortensen, 2018; Grøsvik et al., 2018; Kanhai et al., 2020) implies that Arctic fish are no exception to such exposure. However, for Arctic fish species, few publications on ingestion or accumulation of MP exist so far (Leclerc et al., 2012; Nielsen et al., 2014; Bråte et al., 2016; Fischer and Scholz-Böttcher, 2017; Kühn et al., 2018; Morgana et al., 2018; de Vries et al., 2020; Granberg et al., 2020). The results of those Arctic field studies, combined with evidence of ingestion and accumulation of MP in fish from other areas (Gall and Thompson, 2015; Lusher et al., 2017; Collard et al., 2019; Markic et al., 2020), including fish widely used for human consumption (Neves et al., 2015; Rochman et al., 2015; Lusher et al., 2017; Bessa et al., 2018; Ory et al., 2018; Wu et al., 2019; Barboza et al., 2020), and evidence of MP toxicity from exposure studies (Kögel et al., 2019), highlight that Arctic fish species may be exposed to MP, and the consequences and risks to both ecosystem and human health should be investigated.

3.2.2 Status of global science on microplastics in fish

General trends

To date, MP pollution in fish has mainly been analyzed in the contents of the gastrointestinal tract (GIT). Some studies additionally included the gut walls in the analysis (Fischer and Scholz-Böttcher, 2017; Morgana et al., 2018; de Vries et al., 2020). Results have often been reported as the frequency of occurrence in percent (FO %), i.e., an estimate of the number of contaminated individuals in a population. Additionally, the number of MP in individual fish GITs were reported. In popular scientific settings, they were sometimes presented as the number of MP per individual fish. It is important to be aware of the contexts of these measurements, namely, (1) that it is only the number of MP in the investigated part of the fish (the entire or partial GIT), (2) the size range and quality of MP (such as polymer type, color, or shape) that the applied method was capable of detecting, and (3) its measurement uncertainty.

Counts of MP in the GIT content of fish likely represent a snapshot in time, generally capturing what enters the GIT before it exits through feces during one digestive cycle (Dos Santos and Jobling, 1991; Grigorakis et al., 2017). Fish do not seem to accumulate MP in the GIT over time as seen in some other species (i.e., some seabirds and crustaceans) that have different gut morphologies. Larger MP (2 mm and > 63 µm, respectively) were observed to be expelled with the feces within hours to days in cod and goldfish, respectively (Dos Santos and Jobling, 1991; Grigorakis et al., 2017). The numbers of visually identifiable MP per fish in the GIT were generally low, therefore requiring high sample numbers to assess statistically significant differences. In general, monitoring larger MP in the GIT can provide a rough estimate of MP ingestion rates and differences in such rates depending on factors such as species or locations. However, published data on MP in GIT of fishes so far lack harmonization to the extent that the detection of such factor-dependent differences is only possible in a few cases and within, but not between studies. Mapping of MP distributions and the discovery of which determining factors lead to accumulation and adverse effects will strengthen recommendations for monitoring (e.g., sample numbers, frequency, and station distances for monitoring of MP in fish GIT).

Additionally, small MP in other fish tissues need to be addressed for risk assessment. Importantly, the required methods for analyzing small MP contamination in tissue need research and method development. Once the methods and distribution mapping have been accomplished, then a monitoring program can be set up in a meaningful way.

The importance of the size of microplastics – research areas under development

Studies have suggested that the size of plastics heavily influences the data generated. For example, when studies mapping MP in water were reviewed, it was found that ~80% did not account for plastics < 300 µm, which can be explained by the high prevalence of using the Manta trawl sampling method, with a mesh size of ca. 300 µm (Conkle et al., 2018). This limitation is an issue because smaller size fractions of MP consistently occur in higher particle numbers in environmental samples (Bergmann et al., 2017; Mintenig et al., 2017; Peeken et al., 2018; Simon et al., 2018; Haave et al., 2019; Mani et al., 2019; Brandon et al., 2020). The incidence of small MP cannot be extrapolated from the incidence of larger MP in a straightforward way (Ter Halle et al., 2017; Haave et al., 2019).

Although not the focus of this report, it is important to note that MP were shown to have negative impacts on fish in exposure studies in laboratory-based settings, and that there is more evidence for negative effects of smaller MPs in the low µm ranges compared to larger ones (> 10 µm; Kögel et al., 2019). This is related to the size-dependent uptake in biota and the translocation barriers within biota between tissues and organs and into cells and subcellular organelles. In several studies, the numbers of MP detected in different tissues in exposure experiments increased with decreasing MP size in fish (Jeong et al., 2016; Critchell and Hoogenboom, 2018; Lehtiemi et al., 2018; Gomiero et al., 2020a) and mammals (Jani et al., 1992).

Quantitative analyses of small MP and nanoplastic from fish tissues other than the GIT are likely to be relevant for both seafood safety for human consumption because the GIT is often not the consumed part of the fish, and for the health and population sizes and stability of the fish themselves. If smaller MP and tissues other than GIT are disregarded when fish are analyzed, the obtained frequency of occurrence and individual MP counts per fish will probably underestimate the real situation in fish as a whole organism. However, 10 µm is the current methodological lower size-related threshold for which semi-quantification is possible in larger environmental or biota samples. So far, no published monitoring data are available on plastic pieces below 10 µm, but several field reports on fish show MP occurrence outside the gut contents, in other fish tissues (Collard et al., 2017; Karami et al., 2017; Gomiero et al., 2020a, b). The MP sizes reported in these publications reach hundreds of µm, and Gomiero et al. reported that smaller MP (below 50 µm) were most frequent in salmonid livers and fillets.

Microplastics in Arctic fish

Although fish are considered indicators of ecosystem health (European Parliament, 2000), there are few studies that have investigated the ingestion of MP in Arctic fish (see AMAP definition of the region used for this assessment in Figure 3.3). In bony fish, MP have been reported in polar cod (*Boreogadus saida*; Kühn et al., 2018; Morgana et al., 2018), Atlantic cod (*Gadus morhua;* Bråte et al., 2016; de Vries et al., 2020), Greenland cod (*Gadus ogac*; Granberg et al., 2020), sculpin (*Triglops nybelini*; Morgana et al., 2018), and saithe or pollock (*Pollachius virens*; de Vries et al., 2020; Table

3.3). Although many of the most common fish species consumed by humans from the North Atlantic and Arctic fishery area have been investigated, the applied methods are highly different, compromising the comparabily. For example, either the GIT including content or the GIT content only, were investigated. Because there may be MP entrapped in the gut wall, this might introduce differences in the MP counts. Several of the studies did not target MP analysis, but were feeding assessments in which litter/MP content was a side observation. Some studies relied on visual identification, with or without a microscope, whereas others added chemical identification by FTIR (Fourier-transform infrared spectroscopy). Measurement uncertainties are too high, not always rigourously assessed, and the studies too different and too few to extract certain trends by comparing studies. That being said, we do list some findings.

Occurrence rates of MP in Arctic fish usually ranged 0-3 MP per individual (Table 3.3). One of the Arctic fish studies found higher counts of MP in Greenland cod GIT, in which 12 MP per individual were observed on average (Granberg et al., 2020). This study had a lower detection-size limit (20 µm) than most other studies, suggesting that the methodological differences in detection capacity may yield different results rather than reflecting field or species conditions. Furthermore, Granberg et al. caught their fish using fishing rods and dissected immediately after catching each fish. When usual fish sampling approaches (with nets and bulk fishing) are used in which fish are quickly hauled from deeper depths, fish discharge their gut contents, likely including MP, from their stomach. This would be different for individual species and might be a crucial feature to consider and control for when quantifying MP in the GIT. Additionally, in this study, cod containing the highest number of MP were found closer to local pollution sources. Finally, Morgana et al. (2018) found higher ingestion rates in demersal sculpin compared to pelagic polar cod. However, because of the scarcity of studies, no general conclusions can be drawn yet. It is not clear if the variation is due to the species differences, environmental factors, or the methods applied. Uncertainty and recovery analysis of the applied methods are often lacking.

There are many possible pitfalls caused by a lack of harmonization in the Arctic studies. For example, Kühn et al., 2018 described a low incidence of MP in polar cod compared to Morgana et al., 2018 despite a lower detection limit. It could be because they focused on the stomach content, whereas Morgana et al., 2018 included the entire GIT. However, speculative reasons for this could also be that the Kühn et al., 2018 study did not include microfibers in their analyses to avoid false positives through airborne contamination, which they openly discussed. However, they might have introduced a false-negative error thereby. Although controlling for false positives is important, the study may have excluded real positive samples from their accounts. Therefore, it is important not only to subtract contamination from results, but to keep contamination as low as possible. Real environmental differences may also be the case because the polar cod in the two studies came from different locations. Bråte et al., 2016 observed geographical differences within their study, in which no MP were observed in Atlantic cod from northern Norway (the Varanger and Lofoten areas or in the vicinity of the capital, Oslo), whereas Atlantic cod from the harbor of the second largest city of Norway, Bergen, contained MP (Bråte et al., 2016). One highly speculative hypothesis could be that Bergen, with its rough shoreline on the west coast of the European continent, might comb plastics out of the Gulf Stream. This is an example of how fish may be used to explore larger patterns in MP in relation to shorelines and major current systems.

Table 3.3 Overview of available analysis data of microplastics in Arctic fish.

Species	Location	Fish [N]	FO [%]	MP per individual [N]	Lower detection limit	Methodology	Reference
Polar cod (*Boreogadus saida*)	Eurasian Basin, Svalbard	72	2.8	0-1	> 35 µm	Stomach content, visual inspection, suspected MP by FTIR, fibers not included	Kühn et al. 2018
Polar cod Sculpin (*Triglops nybelini*)	North-eastern Greenland Northern Greenland	85 71	18 34	0-1	> 700 µm	GIT and content alkaline digested, visual inspection, > 700 µm by FTIR	Morgana et al., 2018
Atlantic cod (*Gadus morhua*)	Varangerfjord and Lofoten, Northern Norway	58 56	0	n/a	N/A > 3.2 mm reported	Stomach content, visual inspection, suspected MP by FTIR	Bråte et al., 2016
Atlantic cod Saithe (*Pollachius virens*)	Iceland	39 46	20.5 17.4	0.23 0.28 On average	> 80 µm	GIT and content alkaline digested, visual inspection, FTIR	de Vries et al., 2020
Greenland cod (*Gadus ogac*)	Western Greenland			12 ± 6	> 20 µm	GIT, visual and FTIR on selected particles	Granberg et al., 2020
Greenland shark *(Somniosus microcephalus)*	East, West, Southwest Greenland	30	3.33	0-1	> 1 mm	Stomach content, visual examination	Nielsen et al., 2014
Greenland shark	Svalbard, Norway	45	3	N/A	> 1 mm	Stomach content, visual examination	Leclerc et al., 2012

Because the available data are still scarce but in high demand, we list several other ongoing studies on MP contamination in Arctic fish that we are aware of, for future reference:

- The Nordic Council of Ministers has funded a Nordic/Iceland/Faroes investigation of MP in fish, addressing the viability of using ongoing fish stomach monitoring for MP plastic monitoring (project leader Catherine P. Chambers) and method development for the extraction of MP from cod stomach content.
- The Institute of Marine Research (Bergen, Norway) is currently analyzing haddock (*Melanogrammus aeglefinus*) from the Barents Sea for MP using methods that account for plastics above 10 µm, and experimentally below that, in fillets and liver, funded by the Norwegian Ministry of Trade, Industries and Fisheries (project leader Tanja Kögel).
- Researchers in Canada from Environment and Climate Change Canada (ECCC), Department of Fisheries and Oceans (DFO), and the University of Toronto are quantifying MP in Arctic char (*Salvelinus alpinus*) from the Cambridge Bay region of Nunavut, and researchers from the Nunatsiavut Government and Memorial University of Newfoundland are studying Arctic char and turbot (*Scophthalmus maximus*) from Nunatsiavut in Labrador.
- FACTS, a consortium financed by JPI-Oceans, will be investigating the “Fluxes and Fate of Microplastics in Northern European Waters,” including cusk (*Brosme brosme*) and Atlantic cod from the Barents Sea (project leader Jes Vollertsen; fish work package leader Tanja Kögel).

Sources

We know very little about the sources of MP to fish in the Arctic. The current stage of this research field is immature, and quantification and contamination characterization still need considerable method development. However, there are some indications suggesting MP travel to the Arctic via water currents (Cozár et al., 2014), precipitation (Bergmann et al., 2019), and as waste from boats and ships, including tourism and fishing, i.e., fishery gear and products of daily living (Bergmann et al., 2017; Nashoug, 2017; Falk-Andersson and Strietmann, 2019). The input from wastewater outlets, both with and without treatment, has been investigated in the Arctic (Magnusson et al., 2016; Granberg et al., 2019; von Friesen et al., 2020). Furthermore, loss of plastic litter from landfills might play a role (Granberg et al., 2020). The relative importance of local and distant pollution sources for microlitter needs further investigation. The great connectivity between the Arctic ocean and adjacent seas, through the FRAM and Bering straits may play a role. Another possibility is transport by marine organisms from more polluted areas (van Franeker, 2011; Provencher et al., 2018; Bourdages et al., 2021). Considering the food web, MP in prey organisms, such as plankton, need to be quantified.

Conclusion and research gaps

In summary, information on MP pollution in Arctic fish is scarce, and studies show high variation, both in the applied methods and the results. The studies do illustrate that all investigated species to date in the Arctic ingest MP at some level. Little can be concluded yet about sources, geographical distribution, and species dependency. Globally, small MP < ca. 500 µm in fish and MP in parts of the fish other than the GIT were only analyzed in a few publications because of the expensive equipment and expertise necessary and not available everywhere. Microplastics below 10 µm have not been analyzed at all in wild fish because of methodological challenges, even though there is evidence from exposure studies that such small MP might pose both environmental and human health risks. Because of the scarcity of data, we conclude with a call for more research to fill in the gaps about the distribution, composition, and extent of MP contamination of fish in Arctic ecosystems.

We identified the following major knowledge gaps, which we suggest working on in the coming years:

- Geographical distribution of MP in fish as related to MP in water, sediment, and diet
- Measurement uncertainty/recovery testing of sample preparation and analysis methods
- Accumulation quantification of MP in different species and tissues, throughout the food chain, including identification and principal component analysis of parameters influencing MP ingestion
- Suitable indicator species and tissues applicable to the Arctic ecosystem
- Effects of environmentally relevant amounts and combinations of MP on key species
- Roles of fish for the fate of MP in the environment
- Vector function of MP for other contaminants

3.2.3. Rationale for monitoring microplastics in Arctic fish

Benefits

Fish form an important link between lower and higher marine trophic levels/food webs, including Arctic ecosystems, and they are considered indicators of ecosystem health. Fish also constitute a significant protein source for human nutrition and are an important cultural component for Arctic peoples. Human health may be affected by MP exposure through air, water, and food, directly, as well as indirectly, by the impacts on the ecosystem (Barboza et al., 2018). Adverse effects of any contaminant that is affecting fish, have an impact on food safety, security, and sovereignty. Thus, MP contamination is of concern to food safety authorities, environmental agencies, food security stakeholders, such as UN organizations, and rightsholders, such as Arctic Indigenous peoples. Based on the Marine Strategy Framework Directive (MSFD; European Parliament, 2008), the European Commission produced a set of detailed criteria and methodological standards, which were revised in 2017 (European Commission, 2017) leading to the new Commission Decision on Good Environmental Status (GES), including: "The amount of litter and micro-litter ingested by marine animals is at a level that does not adversely affect the health of the species concerned."

Limitations

Monitoring fish can be costly for several reasons. Targeted fishing is expensive. When using the GIT content to study MP, scientists can easily team up with local and Indigenous fisheries to collect gut contents. However, when looking for smaller plastic particles that are expected to accumulate in fish tissues, the methods needed for quantifying small MP are time consuming, require high-end instrumentation, clean laboratories, and specialized skills. To initiate this costly endeavor, reasons, and purposes should be clear, planning thorough, and study species and tissues wisely chosen. Before monitoring fish on a large scale, methods generally need to be harmonized, and the methods for smaller MP, developed. Then, contamination levels need to be mapped in baseline studies. Table 3.4 suggests how different objectives could focus on different target matrices for quantitative MP mapping. These recommendations are based on a small empiric amount of data and include feasibility in their rationale. Thus, it is not our opinion that, for example, fillet contamination is irrelevant for ecosystem mapping purposes, but rather that liver should be prioritized at this phase due to the high cost of sample analysis and the established status of liver as an ecosystem indicator for other contaminants.

Recommendations for monitoring microplastics in fish

Based on the summary of knowledge above, experience from monitoring other contaminants, and MP contamination research, our best recommendation for species, data, and tissues are provided below for the establishment of a monitoring program for MP in Arctic fish. Because this field is in its infancy, guidelines are likely to adapt according to future insights, but we wish to seize the opportunity to foster harmonization across the Arctic at this early stage. In the coming years, more studies will probably use harmonized methods, and thus, we will be able to form more specific, evidence-based recommendations to address a series of questions related to monitoring litter and MP in fish as related to environmental and human health. To answer specific questions and use resources in a meaningful way, monitoring methods need to meet specific objectives, which will differ, depending on region, agency, purpose, etc. Monitoring methods will also need to target specific matrices (Table 3.4).

Table 3.4 Target matrix per mapping purpose.

Tissue	Ecosystem	Human health
Gills	X	
Gut	X	
Fillet		X
Liver	X	X
Whole fish	X	X

We suggest the following criteria to enable complementarity of monitoring studies based on existing publications (Kögel, 2015; Lusher et al., 2017; Bessa et al., 2019). Microplastic contamination loads should be compared in and across different species, tissues, and geographical areas to enable the determination of suitable indicator species and monitoring conditions. The research field is young, and considerable method development is necessary to achieve meaningful monitoring, therefore we have divided our recommendations for requirements for the data that need to be collected for each study, into two groups.

The “must have” should be feasible to a large number of interest groups and countries. The “beneficial” comprise more cost-intensive goals, which partially require advanced instrumentation and infrastructure, and are not feasible or not necessary for all purposes (Box A).

Box A Required data for monitoring microplastics in Arctic fish

Must have

- Name of researcher
- Species
- Location, including longitude and latitude
- Date: day, month, year, time
- Wet weight and total length of fish
- Liver weight
- Tissue(s) sampled
- Frequency of occurrence of MP per individual/tissue
- For MP > ca. 500 µm: either MP mass or number per tissue weight and particle size group, as mean, with standard deviation and number of samples, median, for individual or defined pooled samples. When reporting for individual fish, include individuals without detected plastic contamination
- Collection, extraction, analysis method applied, including equipment, quality assurance/quality control, limit of detection as MP size and/or mass and measurement uncertainty

Beneficial to have

- Polymer type group (according to Primpke et al., 2017)
- Shape of the MP, as fiber, fragment, or bead
- Color identification of MP
- For particles < ca. 500 µm: either MP mass or number per tissue weight and MP size group, as mean, with standard deviation and number of samples, median, for individual or defined pooled samples. When reporting for individual fish, include individuals without detected plastic contamination
- Sex
- Age of fish
- Depth of collection
- Weather conditions
- Name of fish harvester and boat

In Table 3.5, monitoring and research recommendations are presented separately as "primary monitoring indicators" (required for monitoring) with methods that currently exist and as "secondary monitoring indicators." The latter entails research with activities that point toward a future need of implementation into monitoring. For now, their methods still require development to become robust enough for monitoring, and the baseline mapping of the extent of contamination needs to prelude monitoring. More explanations on the fish species listed in Table 3.5 can be found in the Methods subsection (3.2.4). Currently, no recommendation for sampling frequency can be provided because of a lack of data on MP contamination concentrations and determining factors.

Table 3.5 Summary of monitoring research recommendations for microplastics in Arctic fish.

	Primary monitoring indicators	**Secondary monitoring indicators**
Monitoring	- For MP > ca. 500 µm: GIT content analysis with minimum suggested sample size 50 individuals per station (representing one ecological niche, spreading depending on environmental condition variation and migration pattern of species) and species - Salmonids (trout, char, salmon) - Polar cod - Sculpin spp.	- For MP > ca. 500 µm: GIT content analysis with minimum suggested sample size 50 individuals per station and species: - Capelin (*Mallotus villosus*), flounder, cusk - Identification of a deep-water fish species that can be regularly assessed for plastic ingestion - MP content in muscle and liver of said indicator species, including small particle sizes
Research	- Development of methods to quantify MP in muscle and liver of fish - Development of methods to quantify nanoplastics in fish tissues - Correlation of chemical contaminant data with MP exposure	

Table 3.6 Summary of the estimated costs combined with rationales for the recommended actions.

0 - already in place $ - relatively inexpensive, synergy with ongoing projects $$ - networks and capacity need to be developed $$$ - sampling networks, processing capacity, reporting need to be developed		
Recommendation	**Cost**	**Rationale**
Gastrointestinal tract (GIT) MP content analysis in commercial fishes (cod, salmonids) for MP > ca. 500 µm	$	Existing research programs and collaborations should be established with fishing fleets, such as those assessing population size and chemical contamination, making it relatively easy to add sampling for MP pollution to the workplan. Minimal costs would be added to cover the costs of collection and processing the GIT content for plastic pollution specifically.
Determination of plastic ingestion in small scale fisheries	$	Community-based sampling can be implemented to sample species that are harvested by Northern and Indigenous communities. Addition of minimal costs to implement plastic pollution monitoring to cover collections and the processing the GIT content for plastic pollution specifically. There are also several regular research cruises that could be used to create synergy for monitoring. For example the Institute of Marine Research, Norway, has been registering litter with bottom trawl and trawl and estimating fish population sizes during the scope of their "ecosystem cruise" in the Barents sea since 2010 (Grøsvik et al., 2018), and during their "winter cruise" covering the ice free areas Southwest, East, and South of Svalbard in February/March.
Establishment of time trends in fish MP	$	This is best initiated as a subset of the above-mentioned activities to be repeated at the same station at regular intervals. This should be established annually when possible until power analyses can be used to examine sampling frequency questions.
MP content in fillet and liver, method development for small MP quantification	$$	Analyses of MP content in liver and fillets can begin immediately, methodologically, but existing methods are expensive, and recovery rates below 100 µm are unstable. Method development for small MP is already in progress in many laboratories, and several peer-reviewed articles have been published. However, these methods are largely at a semi-quantitative stage. To enable proper risk assessment, necessitating toxicological tests with realistic environmental concentrations, the concentrations need to be determined, including quality assurance with ring testing and measurement uncertainty determination. That work has been started by several initiatives, e.g., from QUASIMEME Laboratory Performance Studies on MP, European Commission JRC/BAM inter-laboratory comparison (proficiency testing) on MP, and the H2020 Harmonisation Call (CE-SC5-29-2020).
Development of methods for nanoplastics quantification	$$$	It has been shown that nanoplastics have negative effects in exposure experiments. Method development for nanoplastics analysis is ongoing but poses large challenges because the particles adhere to all surfaces and are easily dissolved in the attempt to extract them from biotic matrices. Detection in one biotic matrix has been published (Correia and Loeschner, 2018).

3.2.4 Methods

Fish species

Previously recommended criteria (Bessa et al., 2019) for selecting appropriate species for MP analysis were species that (1) occur naturally with high abundance and wide geographic distribution, (2) are easy to sample and process in the laboratory, (3) are already used as bioindicator/for biomonitoring in other studies related to marine pollution and monitoring international schemes, (4) have ecological and socioeconomic relevance, and (5) cover several ecological/functional niche roles, feeding guilds.

In the light of this previous list, combined with specific Arctic needs and the status of the research field, mapping programs at this stage should focus on species that are:

- widespread, to collect baseline data across regions to understand trends and sources over time and space;
- stationary, to reflect regional/habitat differences;
- consumed by humans to address human-health risks with the following considerations (1) most prevalently used wild fish by Arctic residents for sustenance, (2) most commercially used wild fish because many people will be exposed, and trade restrictions might be established;
- shown or likely to ingest greater amounts of MP, i.e., of high-trophic level because that increases contaminant accumulation, or benthic feeders because more plastic contamination is expected in the sediments compared to the water column or the surface; and
- key species of ecosystem importance.

Given the above considerations, we recommend polar/Arctic cod and sculpin for mapping of MP pollution in fish because they have already been shown to ingest plastic and are incorporated into other pollutant monitoring programs, combined with other salmonids. These species are also commonly consumed by humans in both sustenance and commercial settings and occupy different habitats.

Salmonids and polar cod are regularly sampled by researchers, commercial fishing, and Indigenous and local community members. Therefore, adequate sample sizes (> 50 individuals) can be obtained relatively easily and would allow for rigorous statistical analysis across the Arctic. Salmonids live in diverse ecosystems from freshwater land-locked lakes to sea-run coastal and offshore marine environments. Polar cod additionally are ice-associated because they spawn below the ice edges and feed on invertebrates on the underside of sea ice (Huserbråten et al., 2019). Polar cod also form a core component of the Arctic food web and are relied on by many fish, mammals, and bird species in the region.

Additionally, the Arctic sea ice has been reported to contain high levels of MP particles (Obbard et al., 2014; Peeken et al., 2018; von Friesen et al., 2020). To better understand the effects of melting sea ice on MP in biota, levels of MP taken up by polar cod should be monitored over time because this would allow the study of MP pollution in the context of years of larger and smaller ice melting periods and climate change. Stationary benthic species most appropriate according to these criteria will differ regionally within the Arctic. For example, Arctic sculpin *(Myoxocephalus scorpioides)*, haddock, and cusk would be examples of fish that fit all the criteria in the Barents Sea, whereas Arctic char would be appropriate in North America. Flounder species, such as plaice (*Pleuronectes platessa)*, might be useful for areas closer to the shorelines in some regions. Capelin is already part of regular monitoring for other contaminants in the Arctic and a basis of the food web for larger predatory fish. Each species will represent a different habitat and therefore different environmental impacts, MP sources, and transport pathways.

Sample collection

Samples can be obtained by dedicated cruises, which is often the best way to get enough samples with specific characteristics. However, for commercial species, commercial fishery vessels can be used as a cheaper alternative with the additional benefit of being representative for the market. Also, existing regular cruises, such as those undertaken for population estimations and legacy contaminant surveillance should be used for synergy.

When samples are collected, detailed information regarding location (oceanic region, latitude, longitude, distance to coast), date, time, sampling depth, sampling equipment (including description of materials used, i.e., PP/PE nets, device dimensions, and deployment procedures), and weather conditions should be obtained (Box A). Fisher's names and vessel ID should be reported. For samples collected by fishery, it has proven critical to prepare clear instructions on a preprinted sheet with boxes to record necessary data on the boat and to attach to the samples. Fish can be delivered whole and frozen to the laboratory, packed into single bags to avoid bulk freezing. Immediate bleeding through a cut into one of the gill sets is common practice on commercial fishery vessels, and if this is not desired, the presence of technical research staff might be necessary on the fishing boat. However, allowing routines to be followed could increase collaboration.

The question on how many samples represent a species or an area can only be answered after assessing what the individual variability of the MP contamination is, the context of the study and questions to be addressed, followed by a statistical power analysis. As recommended by OSPAR and MFSD, 50 individuals collected per site/station for MP analysis is ideal (OSPAR, 2015) and most likely to yield results with statistical power needed for comparisons. The OSPAR data are supported by recent reviews (Hermsen et al., 2018; Dehaut et al., 2019). The number of stations necessary also depends on the mobility of the species in question. The more stationary a species is, the more it will reflect local conditions. Further factors are geological boundaries, size, and age. A variety of ages or sampling areas will increase data variation and the number of samples necessary to achieve statistical power to detect differences. The extent of data variability is an unsolved challenge in MP studies. Therefore, caution should be used with respect to increasing data variability, otherwise the risk of producing uninterpretable datasets increases. With this in mind, sampling numbers should be defined in the context of the questions to be addressed. For example, if inter-lake or inter-fjord comparisons are of interest in a highly mobile species, 50 individuals from each lake or fjord may suffice for this work. If the research question is exploring variability in MP along a single fjord, 50 individuals of a less mobile fish may be needed to address this question. If the spatial scales do not allow for separate sampling of fish, or if the fish population may be highly impacted by taking 50 fish at each station along a single fjord, then another environmental compartment should be considered for monitoring.

At the current state of method development, 50 individuals are an unrealistically high number for contamination quantification of small MP using high-end methods, such as µ-FTIR or pyrolysis-gas chromatography/mass spectrometry (py-GC/MS) because of very long analysis times per sample. Then again, that number may be too low if only large MP in the GIT are quantified. Long-term spatial and temporal monitoring may require a reduced sample size per sampling event because of the intensity of laboratory processing required for monitoring programs (Bråte et al., 2018). Analysis of pooled samples can reduce the total number of analyses but comes at the expense of valuable information, such as individual variation and frequency of occurrence.

In general, the number of individuals per site required is still under discussion. Power analysis of mapping data should determine the necessary number of individuals to be analyzed for each species for monitoring. These calculations should consider the area and purpose of the monitoring, as well as species, age, geography, season, time, and prey/trophic level because all of those may influence the concentrations of MP.

Sample preparation and analysis

For mapping and monitoring, standardized sample preparation methods in the laboratory are of utmost importance. This includes clear protocols to obtain all required information about fish samples but also protocols to prevent/reduce contamination or monitor procedural contamination. Sample metrics: fish should be measured and weighed (total length, weight, liver weight, condition index); sex and gonad development stage should be determined (Box A). Age determination, often achieved by otolith ring counting, is useful to assess if bioaccumulation occurs. If the age relation to size is well-known, age determination might be dispensed of because it can be very time consuming.

Depending on the target tissue and aim of each study, different steps are required. There are several prevalent methods for assessing MP in fish. In general, stomachs (and/or intestines) are dissected out and rinsed externally. Then, the gut content is analyzed with or without including the gut lining. Direct visual inspection or extraction by alkaline or enzymatic digestion can be performed. Studies focusing on ingestion of larger items can use a visual sorting method, but limitations include a high detection limit in terms of MP size and increased risks of procedural contamination from extended exposure.

For studies wishing to target smaller MP (< ca. 500 µm), digestion protocols are required. The protocol used for digestion will be dependent on the matrix composition and the equipment of the laboratory (Lusher et al., 2020). At the current stage of the technology, there is still much room for increasing the quality and reducing the time and costs of these protocols. All digestive agents must be prepared and filtered to remove impurities and to prevent contamination of the samples. Alkaline digestion (KOH /1-2 M or 10%; Lusher et al., 2017) or enzymatic purification (von Friesen et al., 2019), combined with oxidation (Löder et al., 2017) are the prevalent, most successful methods to degrade fish tissue without degrading MP. Current method development sometimes combines several of these approaches. Temperatures and molarity of bases or acids should be kept below 40 °C. Because some plastic types have dissolved with acid digestion, it is now not recommended (Dehaut et al., 2016; GESAMP, 2019). For complex samples with high fat content, method development is still needed and may require a step-wise protocol (Lusher et al., 2020). Choosing a protocol requires that (1) quality criteria are fulfilled, i.e., that the method digests the tissue without harming the plastics; (2) recovery percentages are satisfactory; (3) samples do not become contaminated; and (4) agents used do not cause harm to the environment or humans to the extent that a new environmental problem is generated.

Analysis methods

Visual sorting should only be used for particles > ca. 500 µm. To generate knowledge on whether or not toxic amounts of small size classes of MP are present in fish, method development in this area needs to be driven for the quantification of the smaller size classes, down into the nanometer range. The most promising endpoint analysis methods for fish tissue to date are infrared-microscopy and py-GC/MS (see Section 4.3, analytical methods).

Post-analysis data handling

Stating that a certain percentage of the fish had plastic in their stomachs (FO %), while the average number of particles per individual was very low, might provide an unbalanced representation of the contamination. Both numbers need to be presented. Therefore, the average particle number for all individuals should be provided. Because plastic polymers have different physiological effects depending on their composition (Avio et al., 2015; Booth et al., 2016; Green et al., 2016; Mattsson et al., 2017; Rochman et al., 2017), polymer types should be reported when possible.

3.2.5. Quality assurance/quality control (QA/QC)

Contamination mitigation

For contamination control, the whole chain from sample preparation to analysis needs to be considered. Method development is still in its infancy but first attempts to review and summarize important measures have been published (Bessa et al., 2019; GESAMP, 2019; Brander et al., 2020; Cowger et al., 2020). The following issues are important to consider:

- Ideally, fish should be delivered whole and rinsed with filtered water before cutting and preparing tissue samples inside the clean lab.
- To avoid airborne contamination, ideally, air filtration, sluice, and overpressure should be installed in a clean laboratory, with filter capacities according to the size-related detection limit of the study. A laminar flow bench might be used to further reduce MP counts in the air. Samples should be covered with material other than plastic (e.g., clean aluminum foil) as much as possible.
- To avoid contamination from disintegrating inner organs to fillets, frozen fish should be thawed lying on its side, and fillet samples taken from the upper side. When preparing samples from muscle, rinse before extraction to remove fish scales because they contain biopolymers, which are very similar to some plastic types and could therefore be mistakenly identified as plastic.
- All reagents/fluids used in the sample preparation, blanks, and procedural blanks' analyses should be pre-filtered according to the size-related detection limit and covered to prevent airborne contamination.
- All instruments must be cleaned between individual fish. A wet filter or an open water container can be used next to the dissected organism to control for airborne contamination.
- Plastic gloves and tools should be avoided or controlled for in the sample results. All such materials used during dissection should be analyzed to provide references for polymer identification.
- Results of controls, accounting for fibers and other particles of all reported size ranges, and correction calculations should be reported in detail.

Measurement uncertainties

To compare numeric values on plastic contamination between studies and to relate laboratory exposure studies with quantitative field studies, the mesh size, material, and brand/type of all applied filters need to be reported. Filtrations can be of varying quality, for example, caused by irregularities in filter-pore sizes and clogging, which can lead to both larger and smaller particles in the filtrate when compared with the mesh size. Therefore, the smallest particle and largest particle sizes measured, mean and median sizes, and ideally, additional size distribution indicators need to be provided. Extraction efficiencies, measurement uncertainties, and recovery percentages should be established for each fish matrix and method applied, and procedural contamination needs to be monitored. It is necessary to assess the efficiency of spiking, loss at filtration to equipment such as beaker walls and filters, and digestion efficiency of the protocol in terms of tissue degraded versus plastic degraded.

A new challenge to the field of monitoring MP, which does not exist for soluble contaminants such as mercury or dioxins, is that the particle sizes need to be considered. Small particles especially can be lost during the extraction process. The smallest detected particle size does not equal the limit of quantification (LOQ) because usually not all particles of this size class will be detected, and this effect increases with smaller-sized particles. Therefore, measurement uncertainties, and how they are obtained, should be reported. Although a loss of 5 µm of the surface of an MP of several mm during an extraction procedure will not lead to a change in counted numbers or size classes, the same loss of surface will lead to loss of 18 µm particles when using a 10 µm sieve. Transfer of extracted MP to the endpoint analysis, such as an anodic filter or pyrolysis cup, may contribute to further loss. Analysis itself can contribute with both false positives and false negatives, in addition to the misidentifications of chemical identities.

For good laboratory practice, recovery rates need to be published for particles of the same size range, shape, relevant polymer type, and concentration range as the analytes. If this is not feasible, then the lack of such recovery tests should at least be discussed. For legal purposes, parameters for methods and accuracy, measurement uncertainty, and LOQ are measured and regularly tested by proficiency tests. All of these are defined in accreditation protocols. For MP quantification, such accreditation processes are still in their infancy, but have been initiated by Quasimeme (https://science.vu.nl/en/research/environment-and-health/projects/microplastics-ws-and-ils/index.aspx) and the EU commission/Joint Research center /BundesumweltAMt, Germany, for water (https://ec.europa.eu/jrc/en/science-update/call-laboratories-participate-proficiency-tests-microplastics-drinking-water-and-sediments).

3.2.6 Existing population or contaminants (not microplastics) monitoring in the Arctic

Data from many monitoring programs on legacy and other emerging contaminants and fish population development have been collected for decades and are ongoing. Among others, the purposes are to evaluate (1) the state of ecosystems, (2) the suitability of fish species in an area for human consumption, and (3) the sustainability of fisheries. For example, the Institute of Marine Research in Norway tracks and reports contaminants in seafood on a regular basis, including cod, haddock, saithe, capelin, polar cod, and halibut. Similarly, in Canada, contaminants are monitored in Arctic char, burbot (*Lota lota*), and lake trout (*Salvelinus namaycush*) regularly to inform human health questions under the Northern Contaminants Program (NCP). Sweden conducts monitoring of pollutants in Arctic char in Arctic lakes within the AMAP area. Such programs can and should be investigated and exploited for synergy, such as combined use of resources and cruises (collection and sampling of fishes). Data distribution tools, such as databases, should be explored for their potential to add MP, and sampling stations should be harmonized for correlation studies between legacy and emerging contaminants and MP.

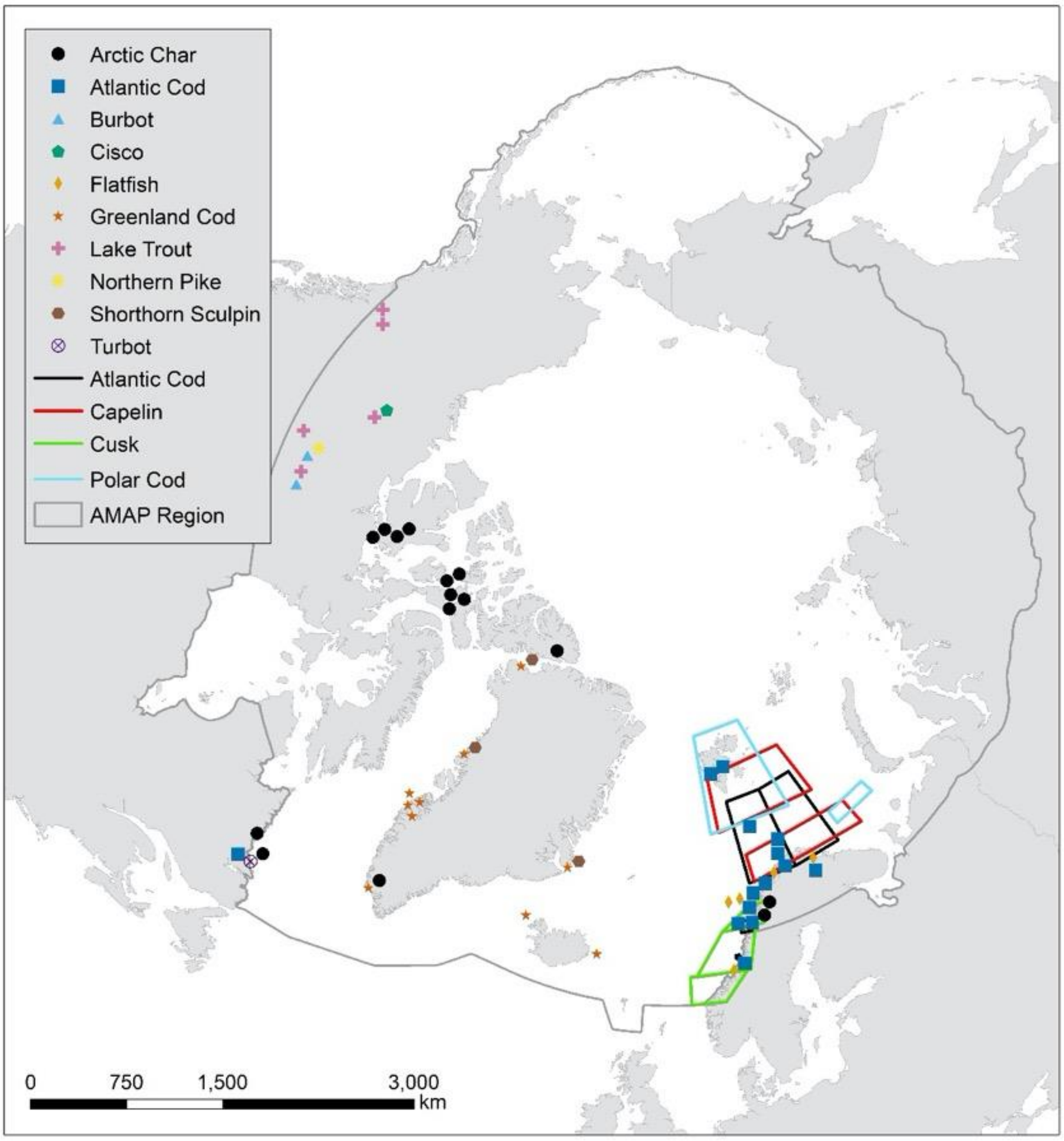

Figure 3.3 Region of interest, which the text referred to as "Arctic" within the circumpolar area. Existing regular fish sampling for other monitoring purposes such as contaminants or fish population monitoring. Repetition interval of sampling is between annually and every third year. Map depicting regular ongoing sampling according to species sampled; see box within figure for symbol coding.

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Photo: Maria E. Granberg

3.3 Seabirds

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3.3.1 Introduction

Seabird exposure to litter and microplastics

Seabirds are vulnerable to litter and microplastics (MP) in two ways. First, seabirds can become entangled in larger debris items such as fishing gear and plastic bags. This can lead to seabird deaths via drowning if the birds cannot resurface to breathe (Battisti et al., 2019; Jagiello et al., 2019; Lively and Good, 2019). Seabirds also collect plastic debris from the water and shorelines and use it for nest building, which can lead to mortality on breeding colonies if birds are trapped in nesting material and starve (Votier et al., 2011; Bond et al., 2012). Second, seabirds can ingest plastic particles and other items, potentially leading to blockage or damage to the gastrointestinal tract (Brandão et al., 2011), reduced body condition, or increased satiation (Connors and Smith, 1982; Dickerman and Goelet, 1987; Ryan, 1987; Sievert and Sileo, 1993; Talsness et al., 2009). Furthermore, plastic pollution ingestion can potentially lead to an increase in exposure to contaminants associated with plastics, as additives or via sorption processes (Teuten et al., 2009; Lavers and Bond, 2016).

Ingestion of non-plastic debris items by birds dates back to the 1800s, but plastic ingestion by seabirds has been reported since the 1960s (Kühn et al., 2015; Provencher et al., 2019). To date, ingestion of plastics or other debris has been reported in 180 of the world's 409 seabird species (Kühn et al., 2015). Of the 64 seabird species in the Arctic (Irons et al., 2015), 40 have been examined for ingested plastics (Baak et al., 2020a), of which 58% have ingested plastic in the Arctic (using the AMAP definition for the Arctic area; Figure 3.4). Although several studies suggest that seabirds experience negative effects from ingested plastic pollution at the individual level, there is no evidence to date that seabirds are negatively impacted at the population level, although limited studies have the capacity to address this question to date.

Seabirds as indicators of plastic pollution – the Northern Fulmar in the OSPAR region

The Northern Fulmar (*Fulmarus glacialis*) is the biological indicator for plastic pollution over 1 mm in the North Sea, where a mandated plastic pollution monitoring program has been in place under the 1992 Oslo and Paris Conventions for the protection of the marine environment of the northeast Atlantic (OSPAR). Originally, the regional Ecological Quality Objective (EcoQO) was developed based on data from Europe, but now also includes data from remote Canadian high-Arctic populations for the 2003-2013 period (van Franeker et al., 2011; Provencher et al., 2017; van Franeker and Kühn, 2020). The current definition of OSPAR's marine plastics EcoQO is: "There should be fewer than 10% of Northern Fulmars having 0.1 g or more plastic in the stomach in samples of 50-100 beached Fulmars from each of 5 different areas of the North Sea over a period of at least 5 years." Northern Fulmars breed along cliffs in the circum-Arctic region, and the protocols developed to track plastic pollution in the North Sea have been applied to Arctic-breeding Northern Fulmars (e.g., Provencher et al., 2009; Kühn and van Franeker, 2012; Trevail et al., 2015; Poon et al., 2017; Snæþórsson, 2018, 2019).

3.3.2 Trends to date, globally and in the Arctic

Based on the plastic monitoring in Northern Fulmars, spatial and temporal trends have been described. Importantly, monitoring Northern Fulmars to date has focused on tracking trends, over time and space, of different plastic pollution types. The mass of plastic pollution in seabirds declines with an increase in latitude, i.e., individuals in the Arctic have less plastic pollution compared to sub-Arctic and temperate locations (Kühn and van Franeker, 2012; Trevail et al., 2015; Provencher et al., 2017). The OSPAR program, which has tracked plastic pollution in the North Sea since the 1980s, has shown that generally the plastic pollution in fulmars increased until about the mid-2000s. Since that time, the average mass of ingested plastic pollution in fulmars has levelled off (van Franeker et al., 2011). It has also been observed in the North Sea and in the southern hemisphere that the levels of industrial plastics in seabirds have generally declined since the 1980s when industry was engaged to alter their practices to prevent the loss of pellets to the environment (Ryan, 2008; van Franeker et al., 2011; OSPAR, 2017).

The foraging strategy of seabirds has been shown to influence the ingestion and accumulation levels of litter and MP (Avery-Gomm et al., 2013; Provencher et al., 2014; Poon et al., 2017). Different seabird species feeding in a similar region can have significantly different levels of litter and MP accumulation. For example, Poon et al., 2017 found that accumulation rates differed among four seabird species examined in a single colony in northern Canada. They were different between groups, but similar within foraging strategies; surface feeders had higher levels of plastic accumulation compared to species that fed primarily in the pelagic zone. These findings highlighted that monitoring data cannot be compared between species, with foraging strategy as the main factor determining data variation. Additionally, sampling in the Arctic region spans decades. With much of the data from some regions collected before the year 2000 and focused on a handful of species that have been collected opportunistically, rigorous comparisons are a challenge. (Figure 3.4).

3.3.3 Benefits of using seabirds as indicators

There are several benefits to using seabird samples to monitor litter and MP pollution in the environment. Globally, seabirds are particularly good indicator species for marine litter and MP because essentially, as they forage, they are integrating information over a relatively large geographical area. Seabirds also breed in colonies that are relatively easy to access for study purposes (Piatt et al., 2007) and can provide sufficient samples in a targeted sampling campaign at a single location, in contrast to the efforts associated with sampling at sea. In some cases, seabirds are harvested, and thus working with community hunters can provide samples for analysis. Finally, seabirds are also found as beached birds in many regions, providing easily obtainable samples with little collection effort (and with the possibility of engaging citizen science and local harvesters).

Specific to the Arctic, seabirds are also useful bioindicators for several reasons. First, there are existing data on diet, reproduction, and contaminants in several seabird species in the Arctic dating back to the 1970s (Barrett et al., 1985; Gaston et al., 2012a). For many species, long-term population monitoring data are available, often along with other data types such as diet data (including stable isotope data to establish trophic relationships) and studies of contaminants (Braune et al., 2006, 2014), enabling co-assessments of several parameters. Second, Arctic-breeding seabird species are also found outside of the Arctic, which thus provides the opportunity to compare levels within the Arctic to regions beyond the Arctic (van Franeker et al., 2011; Provencher et al., 2017). Third, in many locations, community-based researchers can carry out much of the work involved in assessing seabirds for plastic pollution (Provencher, 2014). Fourth, contaminants monitoring in several regions, including the Arctic, already uses seabirds for tracking patterns and trends in environmental contaminants (Dietz et al., 2019), which can potentially provide a platform for new monitoring parameters (Provencher et al., 2015; Poon et al., 2017).

3.3.4 Limitations of using seabirds as indicators

There are also several limitations for using seabirds in monitoring plastic pollution. First, most past studies are limited to plastic and debris that are greater than 1 mm, therefore their current use to study smaller MP is limited. There are some studies that have included smaller size fractions, but these findings are more likely reflecting very local environmental levels more easily sampled via other compartments such as sediments or invertebrates (e.g., Provencher et al., 2018; Reynolds and Ryan, 2018). The indicator species can only be reliably sampled in regions where they regularly breed, are harvested, or carcasses wash ashore—another limitation of seabird studies. Lastly, seabirds can be long-lived and migrate over long distances. Although this can be advantageous in many ways when studying contaminants, it does mean that their route and rate of digestion of plastic pollution are needed to understand the rates of accumulation and what/where their accumulated plastic pollution reflects (Ryan, 2015; van Franeker and Law, 2015).

Seabirds are not evenly distributed along the Arctic coastlines, and therefore there will be geographical gaps in monitoring programs that aim to examine environmental contaminants via seabirds. For example, the western part of the Canadian Arctic Archipelago and the central Russian Arctic have limited numbers of cliff-nesting seabirds, the main type of seabirds used for contaminants monitoring in the Arctic (Figure 3.4). This limits their use in some regions.

3.3.5 Methods to assess litter and microplastics in seabirds

There are several methods for assessing ingested plastics in seabirds: necropsies, regurgitations, and pellet collections being the most common (Provencher et al., 2019). There are benefits and limitations to each of these methods, as discussed in Provencher et al., 2019. Importantly, many of these methods to study plastic ingestion in seabirds can be integrated with diet studies.

All three methods have been applied to seabirds in the Arctic, with the most common method across species and regions being the necropsy method (Baak et al., 2020a). Standard seabird processing protocols exist that can be applied across species and regions (van Franeker et al., 2011; Provencher et al., 2019), including standardized reporting guidelines to ensure that data formats are comparable (Provencher et al., 2017; Box A). These should be applied to all Arctic seabird studies undertaken so that these studies can contribute to the global understanding of plastic pollution trends and patterns in seabirds.

Further steps in the quantitative determination and identification of plastic particles as well as data formats in reporting are described in Provencher et al., 2017, 2019. This includes biological parameters to be reported for each bird, and identification, characterizing, measuring, and reporting of the different types of plastic particles. Further, identification of plastic particles found in the stomachs of seabirds will be of great help to identify the source of the plastic.

3.3.6 Quality assessment/quality control (QA/QC) specific to the compartment/matrix

Most studies consider the gastrointestinal tracts of seabirds, and therefore collections of carcasses via harvest, wreck events, incidental bycatch, etc. can be used as long as the abdomen section has not been pierced or has not decomposed. The recommended QA/QC measures for identifying and characterizing plastic particles applied to seabirds can be limited to general clean laboratory procedures because most seabird studies do not consider plastic < 1 mm (Provencher et al., 2019). When plastics < 1 mm are considered, standard QA/QC procedures for these size classes as well as laboratory blanks are recommended to control for cross-contamination. Associated data corrections should be considered (e.g., Provencher et al., 2018).

Box A: Recommended data collection for the determination of litter and microplastics in seabirds. Based on Provencher et al., 2017, 2019.

Mandatory data for reporting plastic ingestion in seabirds (recommended data to be archived at the individual level)

- Location, including latitude and longitude of sampling
- Date, including day, month, and year
- Sample method (necropsy, regurgitation, pellets)
- Carcass collection method (e.g., hunting, wrecked birds, bycatch, etc.)
- Species
- Tissue sampled (i.e., gastrointestinal tract, stomach)
- Age (including breeding stage)
- Sex
- Total number of user plastics and industrial plastic categories (see Provencher at al., 2017)
- Total mass of user plastics and industrial plastic categories (see Provencher at al., 2017)

Supporting data

- Cause of mortality (with necropsy, where possible)
- Body condition metrics: pectoral muscle size, body mass (when the bird is dry and clean), and subcutaneous fat using the OSPAR protocols as a guide (van Franeker et al., 2011)
- Color of plastic debris, reported in eight broad color groups
- Polymer type proportions per birds and method used
- Total plastics reported by size classes (> 5 mm, 1 < 5 mm, 330 µm < 1 mm, 100 µm < 330 µm)

All of the collected mandatory data, and if possible also the supplementary data, should be reported to an international database (e.g., ICES DOME), so data can be secured and made available in a comparative data format for circumpolar assessments.

3.3.7 Existing monitoring for populations/contaminants in the Arctic

Seabirds are regularly monitored for contaminants in the Arctic, and data from seabirds are used in AMAP assessments of persistent organic pollutants (POPs), chemicals of emerging Arctic concern (CEAC), and Hg (e.g., Letcher et al., 2010; Dietz et al., 2019). In Svalbard, eggs and blood are collected every year from Black-legged Kittiwakes (*Rissa tridactyla*), Glaucous Gulls (*Larus hyperboreus*), and Common Eiders (*Somateria mollissima*) for contaminant monitoring. The Greenland contaminant monitoring program includes a biannual collection of eggs of Black Guillemots (*Cepphus grylle*) and livers of Glaucous Gulls in Central East Greenland (Rigét et al., 2016). Some programs include Environmental Specimen Banks where the samples have been archived for decades and are potentially available for retrospective studies in relation to contaminants from plastic pollution. Depending on the region, seabird eggs or blood samples are the common monitoring tissue, but in some areas (e.g., Canada) standardized collections of adult birds are also undertaken (Mallory and Braune, 2012).

Most countries have standardized population monitoring of the main seabird species, undertaken at varying intervals, from annually to once every 10 years (Irons et al., 2015). In the Arctic, seabird population monitoring is coordinated by the Circumpolar Seabird Expert Group (CBird), under the Conservation of Arctic Flora and Fauna (CAFF) working group (Irons et al., 2015), and thus these programs can be used to implement an integrated monitoring strategy in the context of seabirds and litter and MP.

3.3.8 Recommendations

Due to the variation in foraging ecology of Arctic seabird species, different species can be used to address different monitoring objectives. Importantly, not all species have a circum-Arctic range or are accessible in all regions of the Arctic. By using different species, seabirds can offer a complementary approach that can be implemented throughout the Arctic (Tables 3.7, 3.8, 3.9). The rationale for the following recommendations is based on a number of factors, including existing monitoring programs in waters adjacent to the Arctic (Figure 3.5), sample accessibility, likelihood of positive results, availability of complementary data, and interest for local communities.

Primary recommendations

Northern Fulmar stomachs — A key component for monitoring plastic pollution via Arctic breeding seabirds is the implementation of coordinated collections and processing of Northern Fulmar stomachs. This builds on previous data available in the Arctic and other regions, allows for comparisons between Arctic sites as well as sub-Arctic and temperate locations (e.g., OSPAR), and can be implemented relatively easily based on other research programs (Tables 3.8 and 3.9). A focus on monitoring ingestion pollution by Northern Fulmars would provide trend monitoring in a large proportion of the Arctic (Figure 3.5).

A minimum of 40 individuals should be collected at each site based on a power analysis of the data available from the Canadian Arctic (Provencher et al., 2015). Sampling should be prioritized at sites where historic sampling has been done (i.e., Lancaster Sound and eastern Baffin Island in Canada, Svalbard, Iceland, Faroe Islands, Greenland, Alaska) as well as initiated where possible in other regions with nesting fulmars (e.g., Russia). Sampling should take place later in the breeding season or in the fall to most likely reflect plastic pollution collected in the Arctic around the breeding colonies compared to burdens upon their arrival that may reflect mainly plastic pollution ingested during the wintering period in non-Arctic regions. Specifically, sampling in the autumn should be done when the fulmar chicks have left the nest. Given that historic sampling of Northern Fulmar stomachs has been opportunistic to date, we recommend that coordinated sampling of Northern Fulmars be implemented on an annual or biennial schedule for 8-10 years to establish levels and their variability. Using these data, we can then assess the required future frequency of sampling to detect some percentage of change in levels, as has been done for contaminants (Rigét et al., 2019). In areas of the Arctic in which we do not find dead fulmars on beaches, as long-line fisheries bycatch, and Indigenous harvesters do not collect Northern Fulmars, the method of stomach flushing could be developed as an alternative monitoring method, although comparative studies on flushing efficiency of ingested particles are still needed. Importantly, we recommend that all data collected on Northern Fulmars in the Arctic be entered into an international database (e.g., ICES DOME), so data can be secured and made available for future assessments.

Secondary recommendations

Uria spp. stomachs — *Uria* spp. have been assessed for plastic ingestion in the Arctic and sub-Arctic (Provencher et al., 2010; Bond et al., 2013; Poon et al., 2017). Although litter and MP ingestion in Thick-billed Murres (*Uria lomvia*) and Common Murres (*Uria aalge*) are low (mean ~0-3%; Baak et al., 2020a), likely due to their pelagic foraging strategy, murres are widely hunted and thus can be easily and efficiently sampled (Figure 3.6). Moreover, there are existing plastic ingestion data in several Arctic regions (Canada, Alaska, Greenland, Svalbard, and Russia). Also, they are harvested for subsistence and therefore are likely of interest to communities for tracking plastic pollution in relation to human health. A minimum sample of 60 murres should be collected (Provencher et al., 2015), with monitoring prioritized in regions where historic data exist and/or where hunting regularly occurs and a plastic assessment could be relatively easily implemented.

Gull/skua boluses — There are reports on plastic ingestion in gulls or skuas from Canada, the USA (Alaska), the Faroe Islands, Russia, and Svalbard. Considering the low numbers of gulls in colonies (often a dozen or so pairs per colony), and their declining trends in some regions (e.g., North America; Petersen et al., 2015), gulls are not an ideal candidate for monitoring plastic pollution in the Arctic. However, there are several research questions that could be addressed by examining gull/skua boluses. For example, the collection of gull/skua regurgitated pellets (i.e., non-lethal sampling) should be explored and implemented in colonies where monitoring of populations is already occurring. Examination of pellets will provide information about the potential trophic transfer of litter and MP in Arctic food webs (Hammer et al., 2016). Additionally, to better understand point sources of pollution, gull/skua boluses can be collected around urban centers where waste management actions may be put into place (such as the Marine Litter Regional Action Plan that is currently being developed under PAME). Gull/skua boluses often contain litter large enough to identify to product (Hammer et al., 2016; Seif et al., 2018). Lastly, the use of existing programs that collect eggs from gulls and skuas regularly could be expanded to include plastic-derived contaminants to study how seabirds may be affected by contaminants from plastic pollution (i.e., in Canada and Norway).

Nest incorporation by Black-legged Kittiwakes — Nest incorporation tracks larger pieces of litter and plastics in the marine environment (Votier et al., 2011; Bond et al., 2012). Black-legged Kittiwakes are one of the few widespread and numerically abundant species that build nests in the Arctic (Figure 3.7). Although limited data on nest incorporation of plastics exist for Black-legged Kittiwakes in the Arctic, there are existing data from other regions (Hartwig et al., 2007; O'Hanlon et al., 2017), and a similar Arctic-based protocol could easily be developed and implemented via other existing colony-based programs (i.e., colony monitoring in person or by video and other technologies). A minimum of 200 nests should be monitored at each site for plastics incorporation in nests (Provencher et al., 2015) and could be done through a combination of focal areas observed and photographs via community-based monitoring programs. A protocol should be developed that is harmonized with existing efforts outside of the Arctic and implemented at all colonies where regular colony work is already in place.

Common Eider stomachs — Although Common Eiders are known to have low levels of plastic ingestion (Provencher et al., 2014), eiders are benthic feeders and commonly found and harvested throughout the circum-Arctic region. This species is recommended only in combination with environmental samples and tissue samples for examining plastic-related contaminants. Examination of plastic ingestion in this species down to 300 µm paired with sediment and water sampling in a region would allow for examination of how MP in benthic organisms may be entering the food web. Common Eiders are also commonly harvested for their meat, and studies focused on MP in association with plastic-derived and plastic-associated contaminants are of interest to northern communities. A minimum of 50 individuals per site, paired with locations in which water, sediment, and benthic invertebrates are collected, is recommended based on the low prevalence in this species (< 1%). Given the likely quick passage of MP via the eider, sampling could take place in any season, but should be tied tightly to environmental samples. Additionally, tissues that also reflect local levels should be examined. Any sampling of eiders should also consider preserving tissue samples that can be used to determine concentrations of plastic additive contaminants in tissues most often consumed by humans (i.e., muscle tissue and eggs).

Research gaps — There are currently several knowledge gaps in seabird studies in relation to monitoring trends and patterns in litter and MP. Given the links between plastic ingestion and the potential uptake of plastic-associated and plastic-derived contaminants by biota, the use of Northern Fulmar and Common Eider eggs paired with ingestion studies would provide insights into how biota may be exposed to contaminants from litter and MP. There is also a need for studies on plastic ingestion that explore the links between the ingestion of plastic and the impact at the population level.

Few studies have examined the litter and MP ingestion and accumulation in the Black Guillemot, a widespread, coastal feeding species. In Canada, Poon et al. (2017) found that Black Guillemots on Prince Leopold Island had a 0% prevalence of plastic ingestion in Lancaster Sound, and similarly, Baak et al. (2020b) found Black Guillemots from eastern Baffin Island to have 0% prevalence of plastic ingestion. Plastics have not been found in guillemots in other Arctic regions (Mehlum and Giertz, 1984; Gjertz et al., 1985; Lydersen et al., 1989; Weslawski et al., 1994). Given the need to assess more local impacts in relation to the regional action plans, the development and implementation of litter and MP monitoring in Black Guillemot studies would provide both a monitoring tool that could be implemented in many locations given the dispersed nature of Black Guillemot breeding colonies (they breed in colonies of 100s to 1000s, but can be located every few kilometers along the coast; Gaston et al., 2012b). This species also breeds in the Arctic, sub-Arctic, and temperate locations, therefore providing another tool for Arctic monitoring that can contribute to large scale comparisons.

In the Arctic AMAP region, there are several studies examining litter and MP in Dovekies (*Alle alle*), but most were conducted before 2000 (Baak et al. 2020a). Studies have found fragments, and, notably, burned plastics in stomachs from the wintering regions in Newfoundland, Canada (Fife et al., 2015), and fragments and microfibers in gular pouch sampling at a breeding colony in Greenland (Amélineau et al., 2016). This species may be particularly useful in studying how plastic pollution may be parentally transferred to chicks in the colonies, thus exposing young birds to higher levels of plastic pollution in some regions (Amélineau et al., 2016). Although there are large colonies of Dovekies in some regions, there are no large breeding colonies in North America, and therefore their use as a circum-Arctic indicator species for plastic pollution monitoring is limited.

Although seabird meat is consumed across the Arctic by northern communities, the analytical capacity to examine MP in soft tissues that have translocated outside of the gut are limited. To address future research questions in connection with human health and small MP sizes (nanoplastics), more work needs to be focused in this area.

Table 3.7 Summary of monitoring and research recommendations for litter and microplastics monitoring in Arctic breeding seabirds.

	Primary monitoring indicators	**Secondary monitoring indicators**
Monitoring	- Northern Fulmar stomachs for all litter particles ≥ 1 mm	- *Uria* spp. stomachs for all litter ≥ 1 mm - Gull/skua boluses for all litter around point sources of litter and MP - Nest incorporation of plastic pollution by Black-legged Kittiwakes - Common Eider stomachs for all litter over 300 µm, in association with water, sediment, and benthic invertebrate sampling in the same region - For all studies, polymer types and color groups for ingested litter particles should be assessed when possible These data will be of help to identify the sources
Research	- Black Guillemot stomachs for all litter ≥ 1 mm - Parental transfer of plastic to chicks in species known to ingest plastic pollution - Non-lethal sampling of Dovekie gular pouches delivered to chicks - Northern Fulmar eggs for plastic pollution links to contaminants - Common Eider eggs for plastic pollution links to contaminants - Ingested plastic particles < 1 mm in species vulnerable to ingestion of these small particles	

Table 3.8 Characteristics of litter and microplastics monitoring that could be achieved by seabird monitoring programs.

Species	**Type of litter and microplastics**	**Type of monitoring**	**Types of collection methods**
Northern Fulmar	Ingested floating plastics ≥ 1 mm	Trend monitoring for both temporal and spatial monitoring	Beached birds, bycatch birds from fisheries, harvested birds from hunters
Uria spp.	Ingested floating and mid-water column plastics ≥ 1 mm	Focus on effects monitoring, including links to human health and trophic transfer of MP and plastic associated and derived contaminants	Beached birds, bycatch birds from fisheries, harvested birds from hunters
Black-legged Kittiwake nest incorporation	Litter collected locally for nest building	Source monitoring around areas of concern	Nest observations
Gull/skua boluses	Litter and MP from local areas via bolus collection	Source monitoring around areas of concern	Bolus collection from nest or club sites
Common Eiders	Ingested benthic MP	Focus on effects monitoring, including links to human health and trophic transfer of MP and plastic associated and derived contaminants	Beached birds, bycatch birds from fisheries, harvested birds from hunters

Table 3.9 Summary rationale for recommendations, including estimated costs for implementing programs: 0 - litter and plastic pollution monitoring already in place with regular funding; $ - relatively inexpensive because new litter and microplastic monitoring programs can use existing programs to obtain samples in at least some regions, but need to have some additional capacity to process samples for litter and plastic pollution; $$ - either sampling networks and/or capacity need to be developed to monitor litter and microplastic pollution; $$$ - development of sampling networks, processing capacity of samples, and reporting all need to be developed in the majority of the Arctic regions.

Recommendations	**Program cost**	**Rationale**
Primary Monitoring Indicators		
Northern Fulmar stomachs for all litter ≥ 1 mm - Useful as a monitor in alignment with OSPAR - Offshore surface feeder	$	Existing research programs are already in place on Northern Fulmar colonies, making it relatively easy to add a collection for plastic pollution to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring to cover the costs of collections and processing the birds for plastic pollution specifically.
Secondary Monitoring Indicators		
Uria spp. stomachs for all litter over 1 mm - Widespread and common in the Arctic and beyond - Often hunted - Pelagic feeder	$$	Existing research programs are already in place on murre colonies, making it relatively easy to add a collection for plastic pollution to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring to cover the costs of collections and processing the birds for plastic pollution specifically.
Gull/skua boluses - Useful to monitor around point sources of litter and MP - All gull species regurgitate boluses so can be implemented across several species	$	Gull boluses can be easily collected from around specific areas where there is interest in monitoring point sources of litter and MP. Litter in pellets collected in the breeding season reflects litter uptake during the breeding season if old boluses are removed.
Nest incorporation of plastic pollution by Black-legged Kittiwakes - Limited data available for the Arctic to date - Would contribute to dataset that extends to seas adjacent to the Arctic	$	Existing research programs are already in place on kittiwake colonies, making it relatively easy to add an observation protocol for plastic pollution in nests to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring, but the protocols would need to be developed and implemented. Monitoring of kittiwake nests could be used around urban areas where there is interest in assessing point sources of pollution.
Common Eider stomachs for all litter over 300 µm - Useful monitor in benthic coastal regions - Low plastic ingestion to date, but important subsistence species	$$	Existing research programs are already in place on eider colonies, making it relatively easy to add a collection for plastic pollution to the workplan. Minimal costs would need to be added to implement plastic pollution monitoring to cover the costs of collections and processing the birds for plastic pollution specifically.

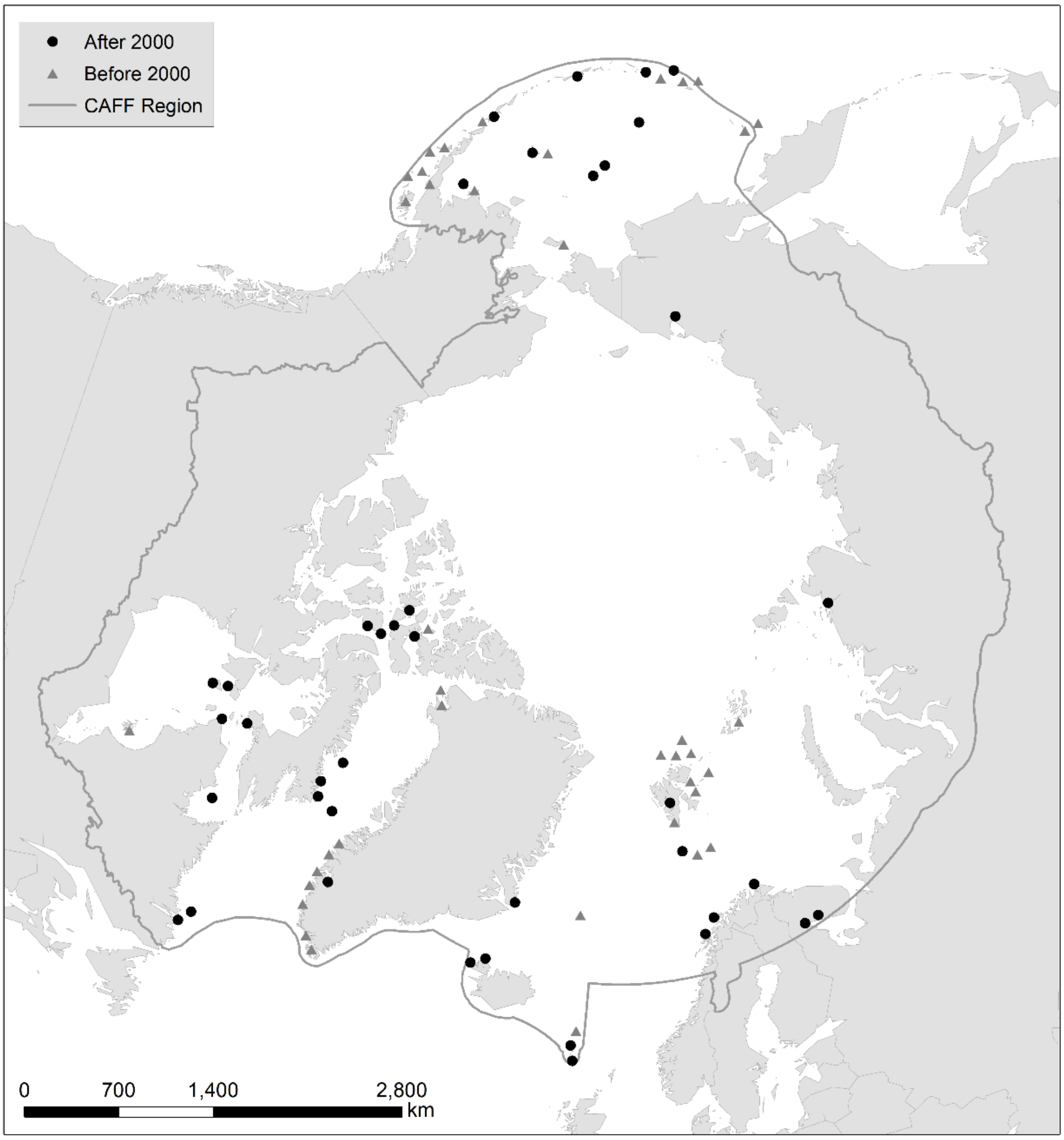

Figure 3.4 Distribution of reported plastic ingestion by seabirds in the Arctic between 1980-2019. Each point represents a sampling location. Overlapping points (i.e., locations sampled more than once) were offset to show all sampling events. Data source: Baak et al.,2020a.

Figure 3.5 Arctic colony locations of Northern Fulmars that may be used to develop a pan-Arctic sampling program for litter and microplastics in the AMAP region. Data source: Baak et al., 2020a.

Figure 3.6. Arctic colony locations of Thick-billed Murres that may be used to develop a pan-Arctic sampling program for litter and microplastics in the AMAP region. Data source: Baak et al., 2020a.

Figure 3.7. Arctic colony locations of Black-legged Kittiwakes that may be used to develop a pan-Arctic sampling program for litter and microplastics in the AMAP region. Data source: Baak et al., 2020a.

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Plastics ingested by Northern Fulmars in Canada (above) and Greenland (below).

3.4 Mammals

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3.4.1 Introduction

Mammals are vulnerable to plastic pollution and other marine litter in two primary ways. First, mammals can become entangled in large items of debris on land and in aquatic environments. Entanglement in fishing gear is by far the most reported interaction for aquatic mammals, with consequences ranging from lesions to death by drowning because mammals are unable to surface to breathe (NOAA, 2014; Panti et al., 2019). Land mammals have also been observed entangled in fishing gear assumed to have beached in areas where mammals feed (Bergmann et al., 2017). Second, mammals can be affected by marine litter via ingestion. Ingestion of plastic and other litter items can have a range of consequences on mammals including blockage or damage to the digestive tract, which can lead to malnutrition and ultimately death (e.g., de Stephanis et al., 2013). Further, high levels of plastic ingestion have been posited to lead to the transfer of contaminants (including plastic additives) associated with ingested litter (e.g., Fossi et al. 2012). The impact of plastics on Arctic biota requires further investigation to provide information that can be used for environmental risk assessment and to address harm.

Most studies to date have focused on assessing the effects of litter and microplastics (MP) on mammals. To the best of our knowledge, there are no existing monitoring programs that use mammals for either trend monitoring or effect monitoring. Studies examining litter, MP, and mammals must first be considered to establish environmental levels in mammals before efforts are taken further. Many mammals play a significant role in Arctic communities as a food source. They are also apex organisms on land and in the sea, thus they may be a relevant matrix for monitoring. These guidelines address both marine and terrestrial mammals.

3.4.2 State of the global science

The International Whaling Commission (IWC) discussed marine litter during three workshops in 2013, 2014, and 2019 (IWC, 2020). Understanding the effects of marine litter on cetaceans globally, and how to work with international partners to ensure collaborative efforts was the focus of these workshops. Mammals are not commonly used for monitoring the presence of plastic in the environment, however some species are monitored annually by the Northern Contaminants Program in northern Canada for chemical contaminants and will be included in Descriptor 10 of the Marine Strategy Framework Directive in Europe. Research to date has mostly focused on the consequences of mammal interactions with plastics, i.e., entanglement and ingestion.

Evidence of marine litter impacts on mammals is available from a variety of published and unpublished sources. Many studies date back to the early 1960s with plastic items and other macrolitter reported as entanglement and ingestion hazards for marine mammals, including baleen whales, beaked whales, dolphins, porpoise, and seals (Caldwell and Golley, 1965; Hofmeyr and Bester, 2002; Lusher et al., 2018; Panti et al., 2019; etc.). As of 2018, 11 out of the 14 families of cetaceans (86 species) were reported to be impacted by marine litter (e.g., Fossi et al., 2018; Kuhn and van Franeker, 2020). Of marine mammal species, 39.8% have at least one documented occurrence of entanglement, and 56.1% have a least one documented occurrence of ingestion (Baulch and Perry, 2014; Kühn et al., 2015; Kühn and van Franeker, 2020). This includes species with different feeding techniques (Panti et al., 2019).

Plastics are reported in digestive tracts of marine mammals, and in some cases, have been attributed to an individual's cause of death (reviewed in Kühn and van Franeker, 2020). There are high geographic, intra- and inter-specific variations in ingestion rates (Baulch and Perry, 2014). Globally, there have been several studies examining ingested marine litter in seals (McMahon et al., 1999; Bravo Rebolledo et al., 2013; Denuncio et al., 2017; Unger et al., 2017; Nelms et al., 2019; Donohue et al., 2019). Importantly, none of these studies were the results of monitoring activities, rather they were research projects or reports produced by strandings' networks.

The absence of macrolitter in some studies does not imply the absence of microlitter (Lusher et al., 2018), although few studies have directly identified MP in the digestive tracts of stranded individuals. Current investigations of MP in marine mammals include seven odontocetes species: Me*soplodon mirus*, *Ziphius cavirostris*, *Delphinus delphis*, *Stenella coeruleaolba*, *Phocoena phocoena, Orcinus orca*, and *Tursiops truncatus* (Lusher et al., 2015, 2018; van Franeker et al., 2018). Only one study on mysticetes, a stranded humpback whale (*Megaptera novaeangliae*), has recorded MP in the intestines, including fragments and threads (Besseling et al., 2015). The study of MP ingestion by marine mammals is a challenging task. It is difficult to obtain viable samples from large cetaceans during necropsies due to large gut content volumes. Obtaining large enough sample sizes can also be a challenge in areas where no harvest takes place. Alternative methods include the collection of scat from pinnipeds; however, it may be difficult to discern plastic ingested by the seal versus atmospheric deposition of MP, especially fibers, on the scat (Dris et al., 2016). Again, none of the investigations on MP has been carried out with a view to monitoring or using mammals as indicators for MP pollution.

Terrestrial mammals are likely to be affected by litter and MP. Globally there are a few reports of plastic ingestion in terrestrial mammals including Arctic foxes (*Vulpes lagopus*; Garrot et al., 1983; Gabrielson, *personal communication*), reindeer (*Rangifer tarandus*), and polar bears (*Ursus maritimus*), which we cover in more detail in the next section.

3.4.3 Information from the Arctic, and trends to date

An assessment of globally available data on cetaceans found an increase in the number of cases being reported over the last five decades (Baulch and Perry, 2014). Although, because none of these studies were carried out for the purpose of monitoring, we cannot discern trends.

Entanglement

Entanglement has been observed for several seal species, such as harbor seals (*Phoca vitulina*), bearded seals (*Erignathus barbatus*), polar bears, and reindeer from Svalbard (reviewed in Øritsland, 1986; Bergmann et al., 2017; Nashoug, 2017; Hallanger and Gabrielsen, 2018). It has been reported that Svalbard reindeer die due to entanglement in derelict fishing gear and other marine litter on the beaches of Svalbard, Norway (Øritsland, 1986; Nashoug, 2017). There is limited information for other Arctic regions. No information is currently available on spatial or temporal trends of entanglement in Arctic mammals.

Ingestion

Of the few reports examining ingested plastic marine litter in mammals in the Arctic, one study has examined plastic ingestion in seals in the Canadian Arctic (Bourdages et al., 2020). The authors examined 142 seal stomachs from the Hudson Bay and Hudson Strait region for ingested plastics above 425 µm. Stomachs of ringed seals (*Phoca hispida*; n = 135), bearded seals (*Erignathus barbatus*; n =

6), and one harbour seal (*Phoca vitualina*) were collected by Inuit harvesters between 2007 and 2019 in collaboration with research programs focused on seal diet and health. The method used for plastic detection was similar to those applied in seabird studies and focused on pieces of plastics > 1 mm (Bourdages et al., 2020).

A different method was used when investigating the stomachs of beluga whales. Stomachs of beluga whales from the Inuvialuit Settlement Region in Arctic Canada were collected by Inuvialuit harvesters (Moore et al., 2020). On average, each whale had approximately 97 pieces of MP (20 µm-425 µm) in their gastrointestinal tract (Moore et al., 2020).

Ingestion of litter and plastics has also been observed in polar bears (Provencher, *unpublished data*, and https://www.hakaimagazine.com/news/polar-bears-plastic-diets-a-growing-problem). A newly published review of polar bear ecotoxicology emphasizes how little knowledge exists on this subject (Routti et al., 2019) and suggests that polar bears are unlikely to ingest considerable amounts of plastics through their prey because they mainly feed on seal blubber. However, as the climate warms, the polar bear diet may be changing, exposing them to more plastics through their diet. Polar bears primarily hunt ringed seals and other marine mammals while on sea ice, but as sea ice begins to melt earlier in the spring season, some polar bears have been recorded moving onshore and opportunistically feeding on a variety of terrestrial prey, such as Snow Geese, Common Eider, and caribou (e.g., Iverson et al., 2014). Indigenous harvesters in Nunavut and the Northwest Territories, Canada have reported that polar bears are frequently observed feeding from landfills and near urban sites. Hunters in Nunavut also report plastics and other debris items in polar bear stomachs and scat (J. Provencher, *personal communication*). This includes towels found in a bear that was dissected by a hunter, and visible plastics in polar bear scat found around community landfills. One-quarter of polar bear stomachs (n = 51) examined in a project conducted in Alaska contained plastics (Stimmelmayr et al., *unpublished data*).

To date, scat collection from mammals has not been widely used in the Arctic to assess MP, although currently a pilot program examining the scat of polar bears for MP is underway in northern Canada (J. Provencher, *personal communication*).

Benefits

Marine mammals typically occupy the top of the food chain and thus are often used as indicators of ecosystem health (Fossi and Panti, 2018; Routti et al., 2019). There are a number of advantages to sampling Arctic mammals to study plastic pollution. First, mammals are food for human consumption, including those captured from the wild. Thus, mammals can provide information on contaminant levels that are likely to be consumed by humans, who also occupy a position at the top of the food chain. Second, when mammals are harvested or found wrecked, digestive tracts and tissue samples can be obtained from targeted individuals. This allows samples to be taken along with other metrics to assess the health of the individual and thus address questions about the impacts. Lastly, mammals are regularly harvested throughout the Arctic, and therefore samples from marine mammals can be obtained cooperatively with communities and harvesters.

Although not all terrestrial mammals in the Arctic are top predators (i.e., caribou and reindeer), they are an important food source for many communities. Therefore, monitoring terrestrial mammals can be done in collaboration with communities and can inform human health assessments interested in the effects of plastic pollution in biota. This is especially true for mammal entanglement in large litter in both inland and coastal regions.

Limitations

Unfortunately, there are many limitations to using mammals for monitoring plastic pollution. One of the biggest challenges is the sheer size of some of the individuals and thus the size of the organs to be examined for litter and MP. These samples can be very difficult to obtain, manage, and work with, and thus examining these samples thoroughly can be challenging. This is of particular concern if microfibers are of interest because minimizing sample contamination is difficult with large samples. Generally, the sample sizes are small in numbers, especially for whales because only a limited number of individuals are stranded or harvested at a time. These small sample sizes are not particularly conducive to rigorous monitoring programs that aim to track trends over time and space. Further, stranded animals are not normally reliable for monitoring plastics because much of the time their stranding is not related to plastic interaction.

Importantly, although there are regions where large number of mammals could be sampled for plastic pollution through local harvests, there are large geographic gaps in which different species are harvested. For example, in Greenland, Canada, and Alaska limited numbers of polar bears are regularly harvested or sampled for contaminants (Figure 3.8), but in other Arctic regions, polar bear samples would be extremely restricted. Similarly, in the Faroe Islands, the pilot whale harvest could be used to access samples to study plastic ingestion, but these would not contribute to a pan-Arctic monitoring plan because this species is not harvested in large numbers in other regions. Lastly, some marine and terrestrial mammals also migrate annually over very long distances, and without a greater understanding of the residence times of plastic pollution, examining long-distance traveling species may not reflect plastic pollution levels in the Arctic.

3.4.6. Methods

Ingestion

Ingestion of plastics is generally reported as an aside of dietary investigations or during the reporting of strandings. In recent years, a targeted approach to understanding the plastic problem has been initiated by several research teams independently. Unfortunately, standardized approaches are not unanimously accepted internationally.

Approaches to assess mammals for ingested macroplastics are few, but these include necropsies, scat samples, and biopsies. Importantly, there may be sampling biases in these methods that are not well understood (i.e., beached animals may contain higher levels of litter and MP than population levels).

Monitoring of MP requires different methods, and emerging research in the last few years has presented parallel approaches to monitoring MP present in digestive tracts and scat. There are benefits and limitations to each method, as discussed by Fossi et al., 2018, and a threefold approach will be beneficial to build a holistic picture of plastic contamination.

- First, necropsies are used to understand the diet of mammals, and most methods can allow researchers to target plastics > 2.5 cm. This is the most common approach for large stranded or harvested cetaceans. This method aims to assess accumulated plastics within the gastrointestinal tract. Using stranding networks can provide further information on marine litter pollution and the exposure of these top predators to plastics. However, stranding networks in the Arctic are limited by low human population density and often hard to access coasts.

- Second, to achieve a more thorough understanding of the risk MP pose to marine mammals, a simple and cost-effective, standardized protocol should be implemented to allow research teams to collect and analyze samples for the presence of litter and MP in a comparable and transparent way, with a particular focus on MP. Necropsies generally follow Kuiken and García-Hartmann, 1991 and therefore could be recommended for MP. Currently, several methods using similar approaches have emerged, such as the protocol presented in Lusher and Hernandez-Milian, 2018 for scat and necropsies. Briefly, the location of marine debris can be reported in three main compartments of the digestive tract to allow for ease of processing the samples and to minimize cross-contaminants: oesophagus, stomach (including forestomach, fundic stomach, pyloric chamber, and duodenal ampulla), and intestines. By dissecting each stomach chamber individually and dividing the intestines into 20 equal sections, it is possible to obtain comparative data between species and individuals (e.g., Lusher et al., 2018). Each section is then analyzed separately and washed over metal sieves to separate plastic pieces from the digestive material (Bourdages et al., 2020). Following digestion (either chemical or enzymatic), the remaining solution can be rinsed and filtered under vacuum onto a filter paper where it will be subsequently analyzed under a microscope. The number, size, color, and morphology of all litter and plastics are then identified per individual using standard metrics for all megafauna (Provencher et al., 2017). Where possible, a subsample of particles will undergo further analysis to confirm polymer identity or plastic presence.
- Third, scat can be used to examine the excretion of plastic pollution by mammals and quantify what litter and MP may be ingested and then pass through mammals. Scat samples can be collected and then processed using digestive techniques aimed at examining MP (e.g., Lusher and Hernandez-Milian, 2018; Perez-Venegas et al., 2018).

Lastly, surveys integrating information from local hunters are useful for detecting litter in mammals. Given that both terrestrial and marine mammals can be entangled in large pieces of litter, and that ingested litter can be observed directly in the stomachs of some mammal species, local and Indigenous knowledge can be used to track patterns. This can be done using standard interview and survey methods with questions focused on what knowledge keepers have observed about litter in animals and on the landscape. These methods have been employed in northern Canada in a study focusing on polar bear health and have highlighted the types of litter bears are vulnerable to ingesting (J. Provencher, *personal communication*).

Entanglement

Mammal entanglement in large items of plastic debris has been observed in the wild. Most instances of entanglement are reported as observations and there is no standard method for observing and reporting this information.

Monitoring the consequences of interaction would be more suitable than monitoring the presence and frequency of macrolitter as a form of marine pollution. Further, it can be challenging, if not impossible to differentiate between entanglement in active fishing gear or marine debris. Similarly, the number of individuals observed entangled may only represent a small proportion. Many are likely to sink and thus never wash ashore or float in areas where monitoring could be conducted. Monitoring of entanglement will require a coordinated network. For example, communities could report observations of entanglement through an app. Many of the existing community platforms could be considered for this. Reporting could follow the OSPAR/NOAA categories.

3.4.7 Quality assurance/quality control (QA/QC) specific to the compartment/matrix

Most mammal studies do not consider plastics < 1 mm and are carried out in the field; therefore, the QA/QC measures are minimal during field sampling. When MP are the target of investigations, a high level of QA/QC must be implemented, and any opening/manipulation of samples should be carried out in a clean or controlled laboratory (see Provencher et al., 2017 dissection techniques). Procedures targeting plastics < 1 mm need laboratory blanks (and where possible field blanks) and should consider data corrections. They should also consider the exclusion of fibers that may come from air contamination (Lusher and Hernandez-Milian, 2018).

Box A: Recommended data collection for the determination of litter and microplastics in mammals. Based on Lusher and Hernandez-Milian 2018 and Fossi et al., 2018.

Mandatory data for reporting plastic interaction with mammals

- Species
- Location, including latitude and longitude (of stranding or biopsy)
- Date, including day, month, and year (should also divide into date of stranding, date of sampling)
- Collection method (necropsy, scat, biopsy)
- Total sample size (i.e., n)
- Tissue sampled (i.e., gastrointestinal tract, stomach, blubber)
- Age (juvenile, adult)
- Sex
- Cause of mortality (with necropsy, and where possible)
- Mean, median, and range for counts and mass of all plastics reported in all sampled individuals by debris category (i.e., foam, fragment, film, fibers, and other; Provencher et al., 2017)
- Size of plastics reported by size classes (Italics are categories from Fossi et al., 2018.)
    - > 2.5 cm (*Macro*)
    - 2.4 cm -1 mm (*Meso*)
    - 1 mm - 300 µm (*Micro*)
    - < 300 µm (*Ultrafine*)
- Polymer confirmation for at least a subset of particles < 1 mm.

Beneficial to have for all data:

- Individual data level
- Color reported in eight broad color groups
- Polymer type for all items
- Body condition

Only possible with large sample size

- Frequency of occurrence of ingested plastics
- Mean, median, and range of mass of ingested plastics/individual

3.4.8 Existing monitoring of mammals in the Arctic

There are a limited number of mammal monitoring programs in the Arctic. In Canada, caribou, polar bear, ringed seals, and beluga are all monitored annually by the Northern Contaminants Program for legacy chemical contaminants. Opportunistic co-sampling with these programs have resulted in two recent studies examining plastic ingestion in seals (Bourdages et al., 2020) and beluga (Moore et al., 2020) in northern Canada. The AMAP Core Programme in Greenland includes annual sampling of polar bears and biannual sampling of ringed seals and reindeer (Rigét et al., 2016). Pilot whales are sampled annually in the contaminant monitoring program of the Faroe Islands, which also included sheep until 2017 (Andreasen et al., 2019). Polar bears and Arctic foxes are collected as part of the legacy contaminant monitoring on Svalbard by the Norwegian Polar Institute, and work is underway to assess plastic pollution ingestion in these species (I. G. Hallanger, *personal communication*).

3.4.9 Recommendations

Mammals are not recommended as a primary monitoring tool for the Arctic based on the current limitations involved with mammal studies (Table 3.10). Given the current evidence, including the low presence, if any, of plastics in digestive tracts, mammals are not a useful indicator of the physical occurrence of plastics in the environment. In cases where the physical occurrence of plastics is observed, future studies should employ harmonized data reporting (Provencher et al., 2017; Cowger et al., 2020).

Polar bears

In several regions of the Arctic, polar bears are harvested in Northern and Indigenous communities. Under the Northern Contaminants Program in Canada and the AMAP Core Programme of Greenland, polar bear tissue sampling is done collaboratively with Indigenous harvesters (Rigét et al., 2016; Letcher et al., 2018). In some regions of Canada, scat samples from bears are also collected to support genomics and diet studies (http://bearwatch.ca). Additionally, Indigenous knowledge surveys in northern Canada have illustrated that harvesters are observing litter in the stomachs of harvested polar bears. Based on the existing efforts to collect polar bear samples with communities, and Indigenous knowledge reports that have observed litter in polar bears, additional samples for examining plastic pollution exposure in bears could easily be added to these existing community-based monitoring programs. Importantly, this type of program could be planned in synergy with existing programs. Thus, reporting to communities could be done by the current programs in a holistic manner concerning contaminants in polar bears, including litter and plastic pollution. Sampling polar bears for litter and MP can also be coupled with sample collection for contaminants. Future efforts to detect smaller size classes of plastics in tissues of bears will be able to inform on effects and human health research and monitoring questions.

Mammal entanglements

Both terrestrial and marine mammals experience deleterious effects because of entanglements in macrolitter in the Arctic. Importantly, this can happen both at sea and on land because macroplastics can accumulate in both environmental compartments. Currently there is no repository or system that reports mammal entanglements in plastic pollution and litter. Given the focus of PAME’s Regional Action Plans on discarded and lost fishing gear, an entanglement reporting tool would allow for the monitoring of this phenomenon and track regional patterns over time and space with a view to removing and preventing this type of litter in the environment. Such a reporting network could be integrated or based on existing marine mammal stranding networks such as NOAA’s Marine Mammal Health and Stranding Response Network (NOAA 2019).

3.4.10 Research gaps

Because of small sample sizes, many marine mammals can be expected to remain understudied across the pan-Arctic, but efforts should continue to explore the fate and effects of marine litter and MP on marine mammals. Studies that explore how mammals may ingest, accumulate, and excrete MP and litter (and thus associated chemical contaminants) will be useful for understanding human exposure to plastics and its compounds in the Arctic.

Mammals throughout the Arctic are harvested for human consumption, therefore mammals should be further considered in monitoring and research of plastic additives and related contaminants, as well as smaller size classes of plastics (i.e., nanoplastics) as analytical tools are developed. Therefore, any sampling of mammals should also consider preserving tissue samples that can be used to determine concentrations of plastic additive contaminants in tissues most often consumed by humans (i.e., blubber, muscle tissue, etc.).

Given the links between plastic ingestion and the potential uptake of plastic-associated and plastic-derived contaminants by biota, investigations into the presence of plastics additives could give indications of plastic uptake (Fossi et al., 2018). Baleen whales have shown promise as an indicator of plastic additives, but this requires coordinated and dedicated research efforts, something that might be hard to achieve in the Arctic.

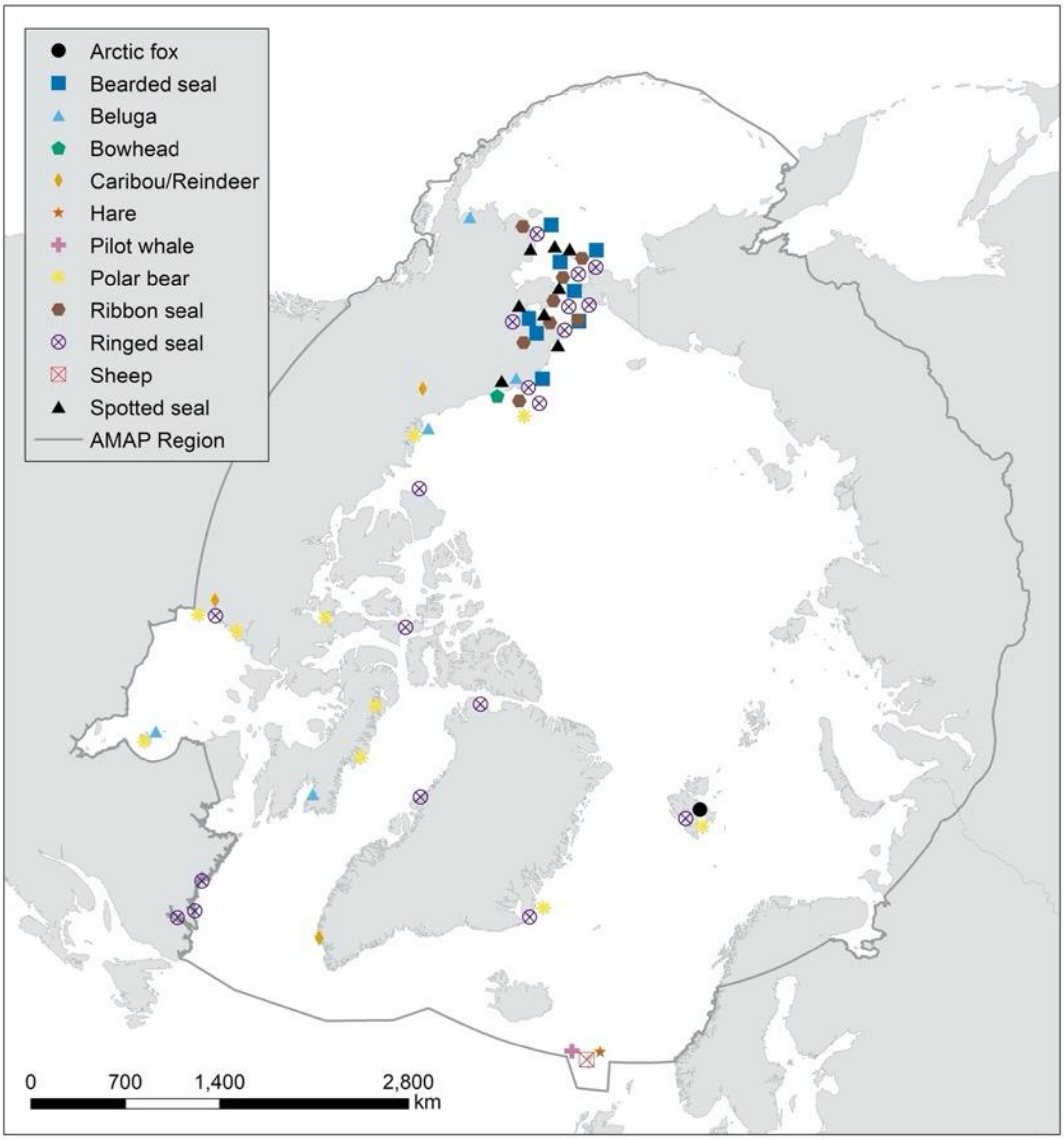

Figure 3.8 Map of existing contaminant monitoring programs using mammals in the AMAP region.

Table 3.10 Summary of monitoring and research recommendations for litter and microplastic monitoring in Arctic mammals.

	1st level (must do)	2nd level (should do/develop)
Monitoring	- Not recommended.	- Polar bear scat/fecal/stomach collections combined with hunter-knowledge surveys for tracking ingested litter and MP. - Reporting network for mammal entanglements.
Research	- Necropsies of land mammals (caribou, foxes, and rodents). - Necropsies of marine mammals (seals, walruses, whales, and polar bears). - Once techniques are available, mammal tissues should be examined for smaller size classes of plastics.	

Table 3.11 Summary rationale for recommendations, including estimated costs for implementing programs: 0 - marine litter and plastic pollution monitoring already in place with regular funding: $ - relatively inexpensive because new litter and microplastic monitoring programs can use existing programs to obtain samples in at least some regions, but need to have some additional capacity to process samples for litter and plastic pollution; $$ - either sampling networks and/or capacity need to be developed to monitor litter and microplastic pollution; $$$ - development of sampling networks, processing capacity of samples, and reporting all need to be developed in the majority of the Arctic regions.

Recommendation	Program cost	Rationale
Polar bear scat/fecal/stomach samples and hunter-knowledge surveys	$	Samples could be acquired through existing research programs where polar bear samples are collected in collaboration with northern and Indigenous harvesters. Minimal costs would then be needed for processing the samples because collections and reporting to communities could be done by the current programs. Hunter surveys of Indigenous knowledge could also be designed and implemented with communities. Studies can also be paired with tissue collections, which may contribute to future studies examining MP and human health questions.
Mammal entanglement	$$	A pan-Arctic tool for reporting mammal entanglements could be established via an online portal or app similar to existing pollution tracker apps (i.e., Marine Debris Tracker) or Indigenous knowledge platforms (i.e., SIKU). This would collect traditional knowledge from northerners on the landscape using pictures and reports.

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Photo: Carolyn Mallory

4.0 Guidance for Analyses, Modeling, and Data Reporting

4.1 Types of litter and microplastics monitoring programs in the Arctic

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4.1.1 Introduction

Environmental monitoring of plastic pollution in the Arctic seeks to characterize changes in the distribution, types, and trends of plastics in a range of ecosystems. Long-term assessment programs often replace one-time projects. However, one-time projects sometimes occur where monitoring efforts are ongoing, which can lead to a disconnect between datasets due to varying assessment methods and an inability to compare data. Long-term monitoring efforts allow for harmonization of methods across the region, familiarity with local conditions and communities, as well as an ability to coordinate singular projects into a coherent set of metrics and goals. In efforts to harmonize monitoring in the North, we argue: (1) long-term monitoring programs are better for establishing environmental trends in the Arctic; and, (2) one-time projects should be linked up with the appropriate monitoring program in the region.

This section introduces several types of monitoring programs with recent examples. The goal is to articulate the breadth of programs, thereby providing governments, scientists, and communities with the knowledge to choose the type of monitoring that best suits their needs. This will also identify existing programs that relevant stakeholders may wish to join or extend. The examples outlined within are not an exhaustive inventory but represent geographical diversity. The types of programs discussed include nationally led, community-based, research stations and observatories, citizen science, species-specific sampling, and opportunistic sampling. We discuss the characteristics of robust monitoring programs versus individual projects to highlight what new, emerging, and developing Arctic plastic pollution monitoring programs should consider in their design and functioning (Table 4.1).

4.1.2 Types of monitoring programs

Government-led

Government-led monitoring programs are carried out by order of ministries or other governmental authorities, or they respond to national calls issued by research councils funded by governments, and they are for monitoring within the governmental jurisdiction. They are often characterized by the obligation to heed certain quality assurance parameters, such as using accredited methods according to international standards, reporting measurement uncertainties, and articulating risk and best practices. Study results are usually published (open access) as technical reports or white papers in the national official language rather than in international peer-reviewed journals, though the latter does occur. Government-led monitoring programs are often driven by the demand to follow or inform national and international laws, such as maximum levels for contaminants in commercially sold food, assessing environmental standards, or conducting population monitoring to ensure sustainable fisheries. They can also inform national policies aimed at achieving the Sustainable Development Goals set by the United Nations. There are several national monitoring programs on plastic pollution, and currently, they tend to focus on macro- and mesoplastics. There are several published national or regional-scale reports on plastics (e.g., MacLean et al., 2013; Reisser et al., 2013; Sundt et al., 2014; Buhl-Mortensen and Buhl-Mortensen, 2017) outlining research happening within a nation's borders.

Although these studies are crucial in understanding the pervasiveness of plastic pollution at a national level, multinational collaborations are also important.

Mapping marine litter in the Norwegian and Russian Arctic seas (MALINOR) is a multinational project funded by the Norwegian Research Council (NFR). Its expressed “main objective is to map areas of marine litter and describe its characteristics in the Arctic in collaboration with Russian institutions with a multi-disciplinary approach” (Salt, 2020). This new, coordinated program will begin by conducting a literature review “from the scientific & grey literature on the distribution of litter in the Norwegian Russian Arctic, identify ongoing activities on this topic both in Norway and Russia, build up a joint Norwegian Russian database, perform mapping using multidisciplinary approaches (robotics, digital solutions, GIS, satellite pictures), collect offshore data using research cruises of opportunity, develop a predictive tool for litter distribution, and importantly, disseminate the findings to the students, public and policy makers both nationally in Norway and Russia and also internationally (e.g., UNEP, Arctic Council)” (SALT, 2020). For a project in development, see the FRAM - High North Research Centre for Climate and the Environment’s scientific program 2018-2023 for plastic in the Arctic (Halsband et al., 2018).

Community-based

Community-based monitoring includes projects that are created, led, and carried out by community groups, as well as projects that are created and facilitated by outside principal investigators but led and carried out by communities. The main benefit of these programs is that they concretely address community concerns about plastics and tend to mitigate or eliminate scientific colonialism in the North where the needs, methods, and goals of southern-based organizations and scientists are often put before local needs. One of the core challenges with such programs is accessibility. Community-based programs often do not possess the capacity and/or funding to maintain a presence in mainstream science circles (e.g., lack of access to web services, conferences, funding, etc.). Furthermore, if there is a desire to bring them in line with other global efforts (i.e., standardizing methods and data regimes), additional resources and capacity-sharing may be required.

An example of a community-based project is Community Monitoring of Plastic Pollution in Wild Food and Environments in Nunatsiavut. This is a project of the Inuit Nunatsiavut Government, led by Max Liboiron (Metis, Memorial University) and Liz Pijogge (Inuk, Nunatsiavut Government) in Nunatsiavut, Canada. Funded by the Northern Contaminants Program since 2018, the program focuses on plastics in traditional food webs and culturally important ecosystems for Inuit hunters and fishers, and local Inuit are employed to carry out the research on their own land. Data are owned by the Nunatsiavut Government rather than the outside researcher. The end goal of the program is for the research to be carried out by the North for the North, minimizing the need for outside researchers.

Research stations and observatories

Research stations and observatories in the Arctic are designed to be permanent or semi-permanent, making them ideal for long-term monitoring projects. They tend to be maintained by governments rather than universities or research groups, although they are often run in partnership with these groups. There are over 100 research stations in the Arctic, most of them listed at the International Network for Terrestrial Research and Monitoring in the Arctic (https://eu-interact.org). One core challenge with these stations is their expense over time.

In 1999, the Alfred Wegener Institute in Germany established the LTER observatory HAUSGARTEN (Soltwedel et al., 2016). Since 2002, the HAUSGARTEN observatory in the Arctic has conducted marine plastic monitoring on the seafloor using towed seafloor photography. It is located in the eastern Fram Strait and comprises 21 stations, which are sampled annually to assess temporal variability in a range of environmental parameters. This regular monitoring has shown that plastic accounted for the highest proportion of litter (47%), and that the proportion and total amount of small-sized plastics increased between 2002 and 2014, indicating fragmentation of plastic litter (Tekman et al., 2017).

Citizen science

Citizen science is the collection of scientific information and observations carried out by the general public, often part of a collaborative project led by a team of researchers. These efforts are usually opportunistic, although they can be more regular if groups return to the same places over time. Long-term citizen science is more likely to occur with community groups or NGOs than with individual scientists. The main benefit of citizen science is that it can minimize costs because citizen scientists are often volunteers. However, two primary challenges arise with citizen science. First, comparing citizen science studies with those following the scientific method can be a challenge because there is often a difference in methodologies to meet their respective goals (Harris, 2019). Second, there are some types of plastic work (e.g., micro- and nanoplastics) that require great care and protocols in collection due to contamination issues, and they may not be appropriate for citizen science work.

The use of the Marine Debris Tracker App is a key example of citizen science being carried out in the Arctic to monitor plastics. This is a free phone application that was created in 2010 through a partnership with the NOAA Marine Debris Program and the Southeast Atlantic Marine Debris Initiative (SEA-MDI) at the University of Georgia (Marine Debris Tracker, 2019). 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 US (Alaska) since 2014. The app continues to be updated and maintained, making it more like a program made up of multiple projects. Citizen science has also been used in short-term projects. In 2016, scientists worked with two tourist cruise operators and their guests to conduct shoreline studies, resulting in a published study (Bergmann et al., 2017). In 2019, a report was released that tested whether commercial ROVs could be used by citizen scientists to map and quantify benthic marine litter, with negative results (Haarr and Havas, 2019). Before the establishment of citizen science programs, we recommend this type of testing be carried out to ensure methodological feasibility.

Species-specific monitoring

Some regional studies of plastic pollution hinge on one key environmental parameter. The decision to use a sentinel species increases the likelihood of comparability of studies over time given the ability to standardize methods suited to the species. This allows individual studies to begin to act as programs, particularly if they are paired with national funding. Sentinel species are usually chosen for their low variability of ingestion rates and non-selective ingestion of plastics, thereby ensuring that temporal trends reflect trends of plastics in the environment. These species should be chosen with care and considered in the context of their ecology. One disadvantage to this method is that it provides a narrow view of environmental plastics generally because a particular species will ingest a particular size of plastic in particular environments based on its body size, range, etc. Therefore, it is recommended that several compartments for monitoring related to species-specific monitoring programs are considered to ensure that collected data will give a more holistic perspective of litter and microplastics (MP) in the environment.

The most developed, species-specific plastic monitoring project uses plastic debris from a seabird, the Northern Fulmar (*Fulmarus glacialis*), and follows the OSPAR and EU-Marine Strategy Directive, thereby employing Ecological Quality Objective (EcoQO) to determine changes in environmental levels of plastics. In Denmark, these studies were conducted between 2002 and 2017. They have shown that 54% of beached fulmars exceeded the EcoQO threshold, and that over the past 10 years, Danish monitoring showed no statistical changes for marine plastic litter in fulmar stomachs (van Franeker et al., 2017). From 2005 to 2014, the same types of studies have been conducted in the North Sea and found that levels of plastic ingestion appear to have stabilized at around 60% of individuals exceeding the 0.1 g level of plastic ingestion specified in the OSPAR long-term goal definition (OSPAR, 2019; see also van Franeker et al., 2005). Other studies at other locations use similar metrics to produce comparable results.

Opportunistic

Although most programs are characterized by advanced planning and stability, some programs are opportunistic. These opportunistic programs tend to be snapshots of an environment at a given point in time, without links or methodological comparability to long-term monitoring programs. Although free research or the seizing of opportunities can provide vital new impulses, insights, and data otherwise not accessed, the coordination of these opportunities and/or the standardization of methods to those from established, long-term programs is key for making these opportunities comparable, and consequently another valuable source of ongoing, low-cost data for long-term monitoring efforts. Such harmonized approaches should be added to research efforts wherever possible.

One key area of opportunistic data is plastic bycatch. For example, between 2010 and 2016, a joint Norwegian-Russian ecosystem monitoring survey saved and analyzed data on plastic bycatch from pelagic and bottom trawling, as well as from visual observations of the surface of water, in the Barents Sea (Grøsvik et al., 2018). This allowed a long-term study of plastics without a specific plastic research design.

Another way to think of a coordinated yet opportunistic program is the way multiple studies can be directly compared when they adopt standardized methods. Using OSPAR methods for shoreline studies, for example, allows studies from diverse areas to be compared, even when they are not otherwise coordinated. Although this does not constitute a program per se, new, emerging, and developing programs might consider how they could opportunistically “adopt” previous studies and data through standardized methods and measurements.

4.1.3 Characteristics of robust monitoring programs

As opposed to research projects, monitoring programs are coordinated, comprehensive, and long term, which enables them to observe longitudinal trends over specific spatial regions. They are usually oriented toward goals, and those goals are reflected in the methods and measures used, which are standardized to allow internal and external comparisons of protocols, data, and results. Ideally, robust monitoring programs should include, but are not limited to, the following: temporal coverage spanning multiple seasons over many years; evaluations of multiple sample media (i.e., biotic impacts, benthic, shoreline, surface water, etc.); specialization in a geographic region; and/or specialization in a particular sample medium across a wide geographic range.

Given the sampling effort, a key consideration for robust monitoring programs is their ability to detect change. Power analyses should be used for future and existing programs and data. Currently, for litter and MP in many compartments, data allowing for power analysis are limited, and only a handful of studies have been done.

Table 4.1 Chart of monitoring programs.

Type	Strengths	Challenges	Example
Nationally Led	• Scale of program matches scale of jurisdiction for action/policy • Likely to have quality assurance parameters • Clear lines of funding and accountability	• Can include large geographic areas • Requires coordination of multiple people/studies • Expensive	Mapping marine litter in the Norwegian and Russian Arctic seas (MALINOR)
Community-based	• Aligns with needs of northern communities • Better chance of eliminating or mitigating scientific colonialism	• Can be difficult for policymakers and scientists to identify these programs • Less likely to meet science community needs and processes, including standardized methods	Community Monitoring of Plastic Pollution in Wild Food and Environments in Nunatsiavut, Nunatsiavut Government
Research Stations and Observatories	• Long-term/permanent so capable of long-term observation • Funded by governments • Excellent sites for collaborative and opportunistic efforts	• Expensive	HAUSGARTEN observatory
Citizen Science	• Inexpensive for accredited scientists • Data can align with community needs and goals if done with local groups • Can include vast geographical reach through wide participation	• Data can be patchy in geographical and temporal terms • Comparison between studies can be difficult • Often not long term if led by outside scientists	Marine Debris Tracker App
Species-specific	• Sentinel species reflect environmental conditions • Can be less expensive if using beached animals • Readily comparable across studies	• Narrow view of one type/size range of plastic	Northern Fulmar and the OSPAR and EU-Marine Strategy Directive to use Ecological Quality Objective (EcoQO)
Opportunistic	• Inexpensive • Novel sources of data • Can be done via standardization of methods for a “program effect”	• Uncoordinated and unplanned; requires after-the-fact coordination • Snapshots of environment	Norwegian-Russian ecosystem monitoring survey of plastic bycatch in trawling studies

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Beach litter survey.

4.2 Data treatment

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4.2.1 General recommendations on data reporting

One of the purposes of formulating standardized monitoring guidelines is to be able to compare observations over time and space. To make observational data comparable, it is important to unify not only the sampling and analysis methodology, but also the data reporting. The use of unified, controlled vocabularies and the setting of standards on the level of data detail for all observers, is one of the critical parts of this process. Although it might be time consuming to adopt a unified data reporting process, it is necessary to establish a solid basis for future data analysis, modeling, assessment, and use.

Data reporting is often seen as a middle step between the detailed raw data collected and stored in individual institutes, and the final target product expected from the assessments.

Under this program:

- data on atmospheric deposition should be reported to EBAS Database[3], operated by the Norwegian Institute for Air Research (NILU)
- data on abiotic compartments (*seawater*, *seabed*, *beaches*, and *sediments*) should be reported to the ICES Environmental Database (DOME)[4]
- data on biotic compartments (*invertebrates, fish, birds*, and *mammals*) should be reported to the ICES Environmental Database (DOME)

Both NILU and ICES 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 has to be reported. In addition, the procedures support the reporting of optional information, depending on the monitoring objectives. In these guidelines, each of the compartment sections (Sections 2.0 and 3.0) have defined what information is optional and mandatory under the objectives of each compartment.

4.2.2 Data reporting to NILU/EBAS

The Norwegian Institute for Air Research (NILU) organizes the EBAS atmospheric database. It was originally designed for the European Monitoring and Evaluation Programme (EMEP) and today it archives data on atmospheric composition from ground stations around the globe, as well as aircraft platforms. Co-operating frameworks and projects include:

- The Convention on Long-Range Transboundary Air Pollution (CLRTAP)
- The WMO Global Atmosphere Watch Programme (GAV)
- The Arctic Monitoring and Assessment Programme (AMAP)
- The EU-project Aerosols, Clouds, and Trace gases Research InfraStructure Network (ACTRIS)

[3] http://ebas.nilu.no/
[4] http://ecosystemdata.ices.dk/

Data submitted to EBAS are protected by a fair-use data policy, although some projects/programs request a more restrictive data policy. The process for submitting data to EBAS is described in the *EBAS Data Submission Manual*[5], which also contains comprehensive *Getting started* documentation.

4.2.3 Data reporting to ICES/DOME

ICES databases and formats

Data on the abundance and geographical distribution of litter and microplastics (MP), as well as relevant ancillary information, can be submitted to the ICES Environmental Database (DOME) in either the Environmental Reporting Format 3.2 (ERF3.2) or the Simplified Format[6].

Depending on the compartment, data should be reported through different mechanisms:

- Litter and MP information for *seawater*, *seabed*, and *beaches* can be submitted as litter datasets.
- Surveys in biota (*birds, mammals, fish, invertebrates*) or in *sediment*, where additional sample parameters should be submitted, can be accommodated as part of the contaminants in biota and sediment formats.
- Seafloor fisheries surveys that deliver data to ICES DATRAS DB in advance, can submit litter data as additional information. Due to the present setup, it is recommended not to request adding new surveys to DATRAS for the sole purpose of litter monitoring. Seabed litter can also be reported through the ICES/DOME mechanism.
- Currently (April 2021), there is no mechanism for the reporting of data from terrestrial soils or from ice/snow. In principle, the ICES/DOME mechanism can handle soil data as sediment data.

The structure of data reporting to ICES requires that a reporting institution within a country reports their data through a single annual submission.

A generic example of the reporting of data to ICES/DOME is found in Appendix 4.1.

ICES litter and microplastics data-specific details: vocabularies, codes, and code types

One of the key tools for ensuring consistent data reporting is the use of controlled vocabularies. The ICES vocabularies organize defined codes as separate code types. In the *ICES Vocabulary*[7], all codes used for data reporting are maintained, including those for litter and MP. New code types or codes can be added to the ICES vocabularies as needed. The following describes certain key code types in connection with litter and MP:

- LTREF[8]: for the classification of litter types, the *Litter Reference List* (LTREF) and respective litter codes from the lists are used.
- MUNIT[9] (with respective VALUE): ICES stores measured data as "number of items" (in the given category), or their "weight per sample," or normalized with sample weight or area.

[5] https://ebas-submit.nilu.no/
[6] http://ices.dk/data/Documents/ENV/Environment_Formats.zip (see ERF3.2 and Simplified_Format_Litter)
[7] https://vocab.ices.dk/
[8] https://vocab.ices.dk/?ref=1381
[9] https://vocab.ices.dk/?ref=155

- Additional information about the litter is stored in separate fields, like LTSZC[10] (litter size category), LTPRP[11] (shape and color mainly), TYPPL[12] (type of polymer), LTSRC (litter source, if known).

Data quality

Prior to uploading data files to ICES, these files must pass a quality verification assessment by a Data Screening Utility (DATSU) that checks if the format and codes are correct.

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[10] https://vocab.ices.dk/?ref=1380
[11] https://vocab.ices.dk/?ref=1403
[12] https://vocab.ices.dk/?ref=1385

Appendix 4.1 Reporting of data to ICES DOME – Generic example

The following example is a generic description of the use of the ICES/DOME Simplified Format. It is provided for illustrative purposes; for a specific submission, the ICES/DOME documentation should be consulted.

The first page shows how data should be organized in spreadsheet table structure for submission. The heading (first line) refers to fields, with more details and descriptions on these fields being presented in subsequent pages.

Table A1.1 Data reporting using the ICES/DOME Simplified Format, generic example

(Line)	RLABO	MYEAR	SHIPC	CRUIS	STNNO	LATIT	LONGI	POSYS	STATN	DEPHU	DEPHL
1	NIVA	2012	AA31	201210	R10	xx.xxxx	yy.yyyy		Fjørtoft R1070BC045		0.05
2	NIVA	2012	AA31	201210	R10	xx.xxxx	yy.yyyy		Fjørtoft R1070BC045		0.05
3	NIVA	2012	AA31	201210	R10	xx.xxxx	yy.yyyy		Fjørtoft R1070BC045		0.05
4	NIVA	2012	AA31	201210	R10	xx.xxxx	yy.yyyy		Fjørtoft R1070BC045		0.05
5	NIVA	2014	AA31	201404	R12	xx.xxxx	yy.yyyy		Finnmark R1298MC037A		0.05
6	NIVA	2014	AA31	201404	R12	xx.xxxx	yy.yyyy		Finnmark R1298MC037A		0.05

(Line)	SDATE	SMPNO	SUBNO	MATRX	LTREF	LTSZC	PARAM	MUNIT	BASIS	VALUE	LTSRC
1	20121006	R10	1	SEDtot	RECO-LT		LT245	nr		291	
2	20121006	R10	1	SEDtot	RECO-LT		LT245	%		87.6	
3	20121006	R10	1	SEDtot			WTMEA	g	W	500	
4	20121006	R10	1	SEDtot			Drywt%	%	W	20	
5	20140415	R12	1	SEDtot	RECO-LT		LT245	nr/kg	D	358.4	
6	20140415	R12	1	SEDtot	RECO-LT		LT245	%		48.3	

(Line)	TYPPL	LTPRP	ALABO	REFSK	METST	METFP	METOA	SLABO	SMTYP	WLTYP	MSTAT	PURPM	MPROG
			NIVA				MIC-FL	NIVA	GE	MO		L	AMAP
		SHP4	NIVA				MIC-FL	NIVA	GE	MO			
			NIVA				GRV	NIVA	GE	MO			
			NIVA				GRV	NIVA	GE	MO			
			NIVA				MIC-FL	NIVA	GE	CF			
		SHP4	NIVA				MIC-FL	NIVA	GE	CF			

Table A1.2 CES/DOME field descriptions, excerpt.

Column	Column definition	Options	ICES Mandatory	Mandatory for assessments	Format
RLABO	Reporting laboratory	http://vocab.ices.dk/?ref=101 http://dome.ices.dk/datsu/rlabo_ls.aspx	**Yes**		See options
MYEAR	Monitoring year		**Yes. Will be created from SDATE if blank**	**Yes**	YYYY
SHIPC	Ship or platform code	http://vocab.ices.dk/?sortby=Description&ref=315	**Yes (minimum requirement is an "AA" code)**		See options
CRUIS	Cruise identifier (series of sampling occasions)		**Yes**		Any character 0–9, A–Z etc.
STNNO	Station identification/Sampling event ID		**Yes**		Any character 0–9, A–Z etc.
LATIT	Latitude (degrees/minutes/decimal minutes or as decimal degrees). Report as WGS84		**Yes**	**Yes**	-90 00.000 to +90 00.000 or '-90.0000 to +90.0000
LONGI	Longitude (degrees/minutes/decimal minutes or as decimal degrees). Report as WGS84		**Yes**	**Yes**	-180 00.000 to +180 00.000 or '-180.0000 to +180.0000
POSYS	Position system	http://vocab.ices.dk/?ref=40	No		WGS84 is assumed if field is blank and GPS is entered. See options
STATN	Station name	Station dictionary - assessments for cont. are based on station names and polygons in the station dictionary	No	**Yes**	Any character 0–9 or A–Z. No ";" or "," or double spaces or parenthesis
WADEP	Water depth (sounding in meters)				0–9
DEPHU	Upper depth (m)		**Yes for water chemicals**	**Yes for water chemicals**	0–9
DEPHL	Lower depth (m)		**Yes for water chemicals**	**Yes for water chemicals**	0–9
SDATE	Sampling date	Multiple years allowed but if blank, the date will determine the monitoring year for file creations	**Yes**	**Yes**	YYMMDD
EDATE	Sampling end date		**Yes for passive sampling only**		YYMMDD
STIME	Sampling time/start (UTC)		No		HHMM

ATIME	Actual time of sampling (UTC)		No		HHMM
ETIME	Sampling end time (UTC)		No		HHMM
SPECI	Species of specimen (WoRMS)	http://www.marinespecies.org/	**Yes for biota data**		Latin name or AphiaID
SMPNO	Sample number/Sample identification for haul or group of individuals/cores/bottles collected at that time/place		**Yes**		Any character 0–9, A–Z etc.
NOAGG	Number of aggregated samples (hauls, sediment cores, or grabs) taken to comprise sample		No		2–99
FINFL	Factors potentially influencing guideline compliance and interpretation of data	http://vocab.ices.dk/?ref=176	No		See options. Multiples allowed when separated with "~" (ascii 126)
SUBNO	Subsample number - individual organism, sediment slice		**Yes**		Any character 0–9, A–Z etc.
NOINP	Number of individuals in sample		**Yes for biota data**		0–9
ORGSP	Origin of specimen	http://vocab.ices.dk/?ref=153	No		See options
SEXCO	Sex code	http://vocab.ices.dk/?ref=45	No	**Yes for some effects parameters**	See options
STAGE	Stage of development	http://vocab.ices.dk/?ref=52	No		See options
CONES	Condition of specimen	http://vocab.ices.dk/?ref=74	No		See options
ASTSA	Animal state at time of sampling	http://vocab.ices.dk/?ref=64	No		See options
NODIS	Number of diseases looked for during a fish disease survey		No		0–9
BULKID	Bulk identification (for individuals only)	Existing related SUBNO. If an individual (or parts thereof) has been analyzed in one or more bulks, insert the SUBNO identification(s) of the bulk(s). Note that BULKID can only refer to a SUBNO within the same sample. See field descriptions for an example. (separate multiple entries with "~" (ascii 126))	No		0–9. Multiples allowed when separated with "~" (ascii 126)
MATRX	Matrix	http://vocab.ices.dk/?ref=55	**Yes**		See options
PARAM	Parameter	http://vocab.ices.dk/?ref=37	**Yes**		See options
MUNIT	Measurement unit	http://vocab.ices.dk/?ref=155	**Yes**		See options

BASIS	Basis of determination	Enter NR if not relevant, otherwise see http://vocab.ices.dk/?ref=65	**Yes**		NR or options in list
VFLAG	Validity flag	http://vocab.ices.dk/?ref=59	No		See options
QFLAG	Qualifier flag	http://vocab.ices.dk/?ref=180	No		See options
VALUE	Value measured		**Yes**		0–9
PERCR	Percentage recovery - to be applied (if thought necessary by data submitter) to the reported value (in VALUE field) at an assessment to give a better approximation of the real value		No		0–9
SIGND	Significant digits reported in VALUE		No		0–9
UNCRT	Uncertainty value		No	**Yes for chemicals**	0–9
METCU	Method of calculating uncertainty	http://vocab.ices.dk/?ref=213	**Yes if UNCRT is reported**	**Yes for chemicals**	See options
DETLI	Detection limit		No		0–9
LMQNT	Limit of quantification		No		0–9
PRFLG	Pressure flag		No		0–9
ALABO	Analytical laboratory	http://vocab.ices.dk/?ref=101	**Yes if methods or QA fields are reported**	**Yes for most parameters**	See options
REFSK	Reference source or key	http://vocab.ices.dk/?ref=171	No	**Yes for some effects parameters**	See options
METST	Method of storage	http://vocab.ices.dk/?ref=200	No		See options
METFP	Method of chemical fixation/preservation	http://vocab.ices.dk/?ref=34	No		See options
METPT	Method of pre-treatment	http://vocab.ices.dk/?ref=201	**Yes for seawater data to show filtered or non-filtered**		See options. Multiples allowed when separated with "~" (ascii 126)
METCX	Method of chemical extraction	http://vocab.ices.dk/?ref=202	No		See options. Multiples allowed when separated with "~" (ascii 126)
METPS	Method of purification/separation	http://vocab.ices.dk/?ref=198	No		See options
METOA	Method of analysis	http://vocab.ices.dk/?ref=173	No	**Yes for most parameters**	See options
AGDET	Age determination	http://vocab.ices.dk/?ref=19	No		See options
SREFW	Source of reference seawater	http://vocab.ices.dk/?ref=154	No		See options

SPECI	In vivo/In vitro test organism or cell line	http://vocab.ices.dk/?ref=351	No	**Yes for some effects parameters**	See options in list "VIVIT"
ORGSP	Origin of test specimen	http://vocab.ices.dk/?ref=153	No		See options
SIZRF	Size class reference list	http://vocab.ices.dk/?ref=303	No		See options
FORML	Formula used in calculation	http://vocab.ices.dk/?ref=296	No		See options
ACCRD	Accredited laboratory for the linked parameter	Y for Yes or N for No	No		Y or N
ACORG	Accrediting organization	http://vocab.ices.dk/?ref=355	No		See options
SLABO	Sampling laboratory	http://vocab.ices.dk/?ref=101	**Yes if SMTYP or other sampling fields are reported**		See options
SMTYP	Sampler type	http://vocab.ices.dk/?ref=152	No	**Yes for passive sampling**	See options
NETOP	Net opening width (m)		No		0–9
MESHS	Mesh size of net or sieve (µm)		No		0–9
SAREA	Sampler area (cm^2) For passive sampling, this is the exposed area of the sampler (membrane). See SMTYP PS-*		No	**Yes for passive sampling**	0–9
LNSMB	Length of sampler (core) barrel (cm)		No		0–9
SPEED	Speed (e.g., trawls) (knots)		No		0–9
PDMET	Plankton (or eutrophication) sampling depth method	http://vocab.ices.dk/?ref=38	No		See options
SPLIT	Sample splitting technique	http://vocab.ices.dk/?ref=50	No		See options
OBSHT	Observation height (from surface) (meter)		No		0–9
DURAT	Duration of haul (minutes)		No		0–9
DUREX	Duration of exposure in days		No	**Yes for passive sampling**	0–9
ESTFR	Estimated water sampling rate (flow) in liters per day		No	**Yes for passive sampling**	0–9

4.3 Analytical techniques for the identification of microplastics

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4.3.1 Background

The analysis of microplastics (MP) is currently performed using different techniques ranging from visual identification of the particles to a comprehensive chemical identification of the polymer type, including additives and adsorbed substances. Based on published reviews (Ivleva et al., 2017; Zarfl, 2019; Primpke et al., 2020a), recommendations (Frias et al., 2018; Gago et al., 2018; Bessa et al., 2019), and existing monitoring guidelines (GESAMP, 2019), we provide an overview of the available techniques for analyzing MP with respect to environmental monitoring.

4.3.2 Optical identification methods

Microscopy

Microscopy-enhanced optical identification of MP in the visual spectrum is one of the most commonly used identification methods. Visual identification of MP has been applied to a wide range of matrices including:

- natural waters;
- sediments;
- soils;
- air (including street dust);
- wastewater treatment plant influent, effluent, and sludge;
- aquatic and terrestrial organisms; and
- human foodstuffs (e.g. table salt, honey, and beer; Primpke et al., 2020a).

In general, guidelines for the visual identification of MP (Lusher et al., 2020; Primpke et al., 2020a) are provided based on visual parameters such as color, color distribution, shape, surface properties such as light reflection, as well as the widths, length, and features of fibers. The majority of studies sort MP into six shape categories: fragments, beads, pellets, films, foams, and fibers (OSPAR, 2015). Previously, visual identification was often used solo, but yielded high misidentification rates if not combined with chemical analysis (Hidalgo-Ruz et al., 2012). Even though most studies reported detection limits of 100 µm or larger, (Primpke et al., 2020a), GESAMP only recommended visual identification in the monitoring of marine ecosystems for particles > 1 mm. However, GESAMP does suggest combining optical microscopy analyses with spectroscopy analyses (see Table 10.10 in GESAMP, 2019). A similar approach was also suggested by Löder et al., 2017, including a size fractionation pre-treatment step into larger (e.g., > 500 µm) and smaller particles (e.g., < 500 µm) prior to sample extraction. Although the smaller particles require sample extraction, the larger particles can be picked manually, assisted by optical microscopy, and identified chemically afterward.

Notably, data of the different studies were presented in highly varying size categories. Part of the underlying reason for this may be the technical lower-size limitations imposed by the applied filtration units for the extraction process. For comparability, harmonization of reported/measured size fractions is necessary.

Compared to more advanced techniques, optical identification is inexpensive because the instrumental costs are low (Primpke et al., 2020a). Combining optical microscopy with digital cameras for image analysis further reduces the personnel costs associated with particle counting. In contrast to some advanced methods, which have specific and costly filter substrate requirements, samples for optical microscopy can be collected on inexpensive filter materials such as glass fiber or polycarbonate (PC).

The overall processing time of a filter imaged for MP was found to depend on the applied guidelines, the filter size used, the sample type (e.g., sediment, surface water), the targeted size classes, and the general distribution of particles (Cowger et al., 2020a; Primpke et al., 2020a; Thaysen et al., 2020).

For this method, it is important to consider human difficulties in differentiating non-polymeric particles and natural polymer-based particles (e.g., chitin or wool) from MP of interest (see Figure 4.1), which may introduce a bias (Hidalgo-Ruz et al., 2012; Zarfl, 2019; Primpke et al., 2020a). Such bias is dependent on the experience level of the investigators and is significantly reduced for very experienced labs. If a chemical analysis of the material is not available, the materials can be tested on their physical behavior by testing the particles with microforceps or a dissecting needle (Lusher et al., 2020). Further, the thermal behavior of the particle can be investigated with a hot needle because plastics melt at elevated temperatures. All these tests yield enhanced results compared to the unassisted use of microscopy.

Nevertheless, the need for experience in the analysis and testing of such small particles increases with the decreasing size of the particles. Furthermore, some reported guidelines for optical microscopy identification of MP exclude the selection of particles exhibiting properties that make identification challenging. This includes particles that are black, brown, white, or clear in color (Wiggin and Holland, 2019). In such cases, the generated data will represent an incomplete picture of the true levels of MP contamination. For monitoring at the current stage, this is an acceptable solution. Still, it is critical that any datasets produced using such methods highlight these issues so that other researchers and end users of the data are aware of the limitations and can account for this when translating monitoring data into practical measures and mitigation actions.

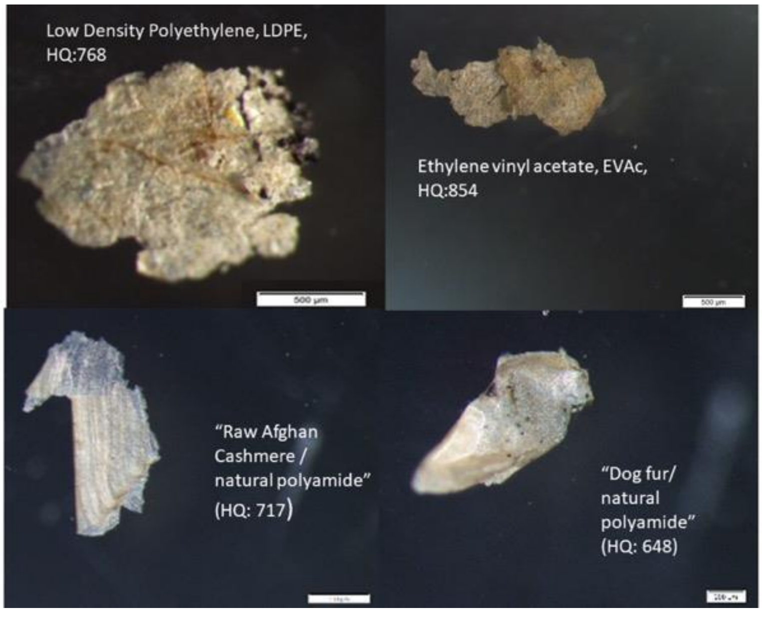


Figure 4.1 Particles sorted as potential microplastics by optical microscopy further identified via attenuated total reflection Fourier-transform infrared (ATR-FTIR) spectroscopy (Haave et al., 2019).

Fluorescent staining of microplastics for microscopy and preselection of particles

The use of fluorescent dyes to stain MP particles is increasingly applied to achieve faster selection of particles and reduce researcher bias (Zarfl, 2019). Staining is typically conducted after any sample fractionation or extraction steps have been conducted to minimize staining of the non-plastic organic material. One of the most applied dyes for MP staining is Nile Red (NR; Andrady, 2011), which is inexpensive and easy to handle. Recently published literature has demonstrated its application for staining MP in various types of water samples, sands, sediments, biota samples, and atmospheric deposition samples (Primpke et al., 2020a) for particle sizes from ≥ 300 µm down to 20–3 µm, thus expanding the range achievable by optical microscopy (Primpke et al., 2020a; Figure 4.2).

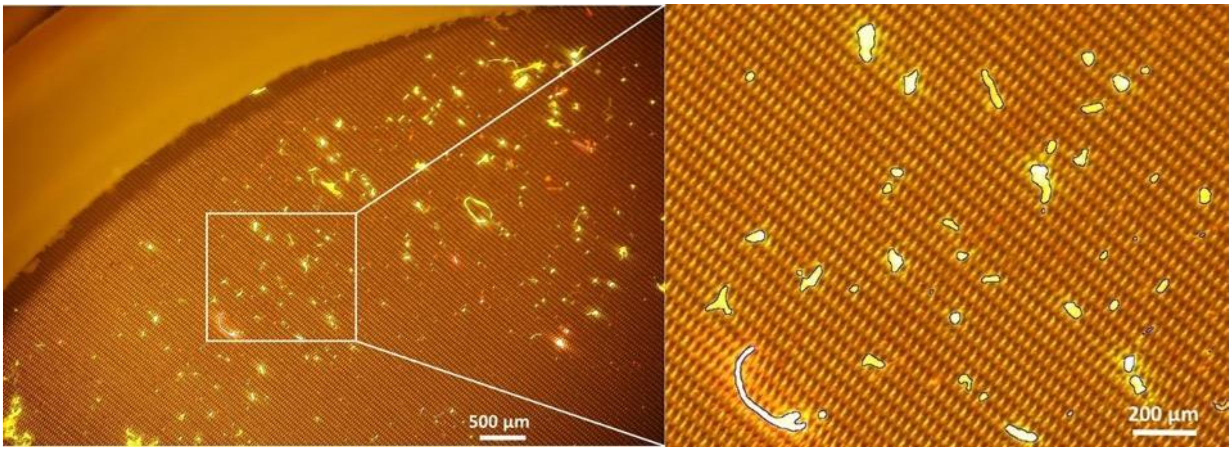


Figure 4.2 Filter showing fluorescent microplastic particles after dyeing with Nile Red (left). Zoomed region showing automated image analysis of individual particles down to ~10 µm. Images produced by SINTEF Ocean.

The major drawback of using NR is its lipophilic nature and therefore its propensity to stain all lipid materials present in a sample (e.g., derived from biota; Cooksey et al., 1987). For this reason, comprehensive sample extraction and cleanup are necessary to remove any biogenic materials and to avoid the potential misidentification of natural materials, e.g., lipid droplets and microorganisms, as MP (Erni-Cassola et al., 2017; Wiggin and Holland, 2019). Currently, a wide variety of sample extraction protocols are in use, including the application of oxidizing agents or enzymes (Primpke et al., 2020a). Another pitfall to consider is that NR can precipitate as agglomerated particles if applied in certain concentrations and solvents, which can lead to confusion with stained MP (A. M. Bienfait, *personal communication*). Additionally, method harmonization is not conclusive at present, especially because there are large differences between recommended optimum concentrations, with literature values ranging from 0.1–2 µg mL^{-1} (Erni-Cassola et al., 2017) up to 1–1000 µg mL^{-1} (Maes et al., 2017).

Nile Red was found to be an effective stain for various polymers ranging from polyethylene (PE), polypropylene (PP), polycarbonate (PC), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyurethane (PUR), expanded polystyrene (EPS), polyethylene-vinyl acetate (PEVA), to polyamide (PA; Zarfl, 2019; Primpke et al., 2020a). Although there is some indication that different polymer types stain sufficiently differently to allow a tentative identification (Maes et al., 2017), a robust characterization equivalent to direct chemical identification methods is not possible. Furthermore, the additional parameters like particle size, shape, and solvents used may alter the staining behavior. Different staining efficiency percentages between 100% and 0%, with variations of co-staining of biological material were obtained, depending on the polymer/solvent combination (Shim et al., 2016; Tamminga et al., 2017). Importantly, the technique has limitations with certain subclasses of MP, including those which are black in color, fibers, and rubber-based MP. Recent work suggests low error rates if the particles undergo FTIR or Raman spectroscopy subsequent to NR staining (Sutton et al., 2016; Maes et al., 2017), but the analysis that followed was often rather time consuming compared (up to one hour for a single Raman spectrum) to other rapid direct chemical identification methods. Still, NR staining is a promising technique to highlight potential particles and guide researchers (Klein and Fischer, 2019) or technical applications toward particles of interest.

4.3.3 Chemical analysis techniques

Accurate and robust chemical identification of MP is crucial for studies such as ecotoxicological risk assessment because the chemical nature of the particles influences the nature of the toxic effect on organisms that have ingested them (Avio et al., 2015; Booth et al., 2016; Rochman et al., 2017; Kögel et al., 2020). Several analytical techniques are available that use either spectroscopy or thermal degradation coupled with gas chromatography-mass spectrometry-based methods for the identification of MP. The main methods used for identifying MP in environmental samples are described briefly below.

Fourier-transform infrared spectroscopy for microplastic analysis

Fourier-transform infrared spectroscopy (FTIR) produces a spectral pattern, called IR-spectrum, representing a fingerprint of the polymer types. The obtained spectra are analyzed by comparison with reference spectra for each polymer type. Those reference spectra are compiled in spectral libraries.

Recently, 161 publications applying FTIR for MP analysis from environmental samples were summarized (Primpke et al., 2020a). These studies used a range of different FTIR technologies, including analysis based on single particles, via handhelds, fiber optics, microscope supported systems (µFTIR) or applied single particle, and µFTIR analysis on separate instruments. For 58% of the studies, attenuated total reflection (ATR)-FTIR on single selected particles (see Figure 4.3) was the method of choice. No sample preparation or mathematical correction are necessary by the operator for this method (Primpke et al., 2020a). Particles are placed in contact with the instrument’s crystal, which is relatively fast, and the analysis is performed without requiring advanced skills by the operator. Spectral analysis is normally followed by library searches (Renner et al., 2019a) via spectral correlation or approaches like machine learning (Renner et al., 2017, 2019b; Hufnagl et al., 2019; Kedzierski et al., 2019).

FTIR microscopy (µFTIR)

In contrast to single particle FTIR, µFTIR combines microscopic imaging and particle-size determination with FTIR. Individual particles down to sizes of ca. 10 µm can be detected. The term µFTIR covers a small range of FTIR analysis techniques. Thus, microscopes are often coupled with an attenuated total reflection (ATR) unit for the selective analysis of either small particles or areas on larger particles. Independent from the ATR unit, reflection and transmission FTIR are applied to particles using various types of FTIR spectrometers (Primpke et al., 2020a).

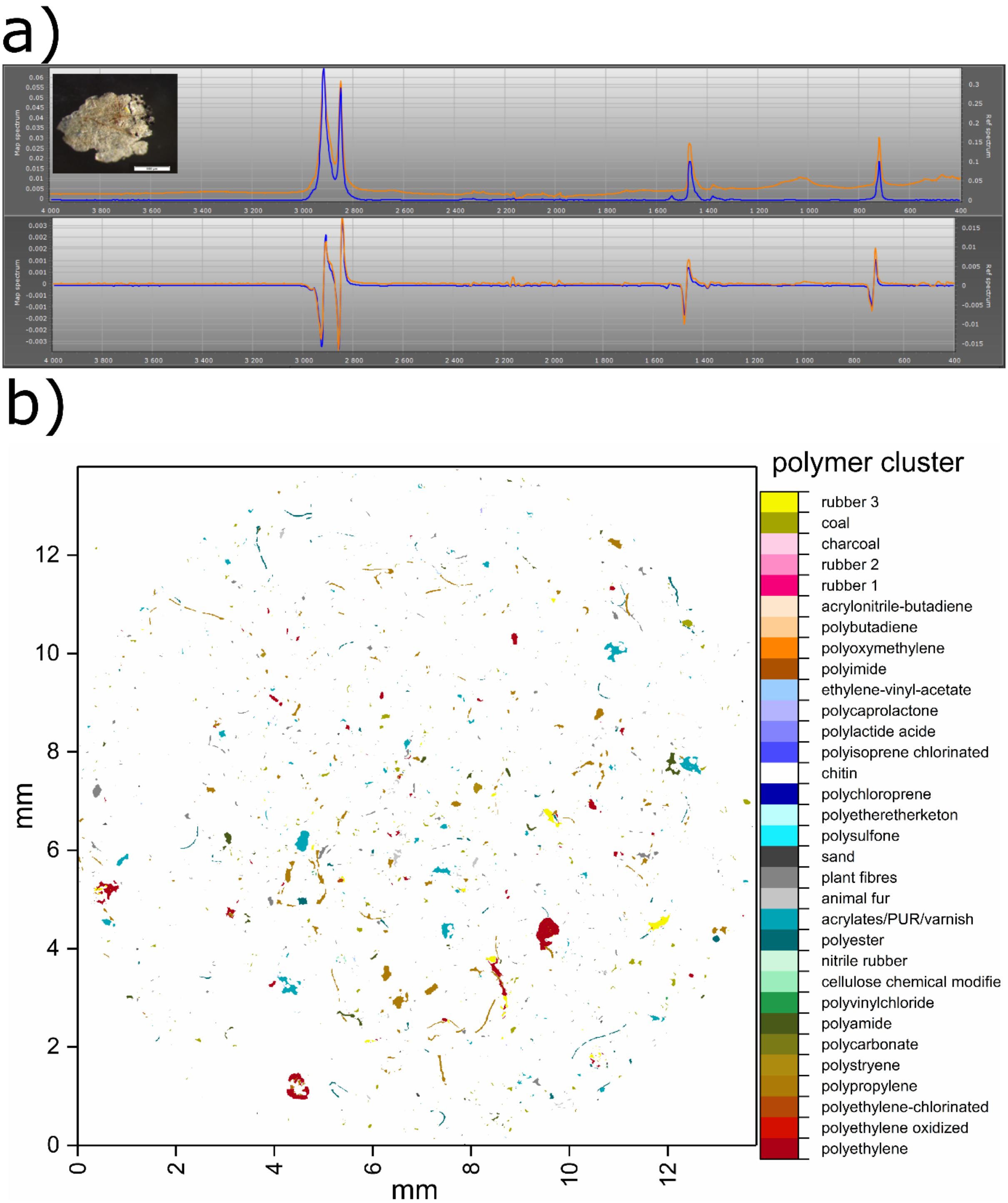


Figure 4.3 a) Particle identified via attenuated total reflection Fourier-transform infrared (ATR-FTIR) spectroscopy using siMPle (Primpke, 2020b) from a sample from the Bergen Fjord (Haave et al., 2019). b) Analysis of the < 500 µm fraction of the same sample from the Bergen Fjord investigated via µFTIR imaging (Haave et al., 2019).

The following drawbacks need to be considered when deciding which method to apply.

- ATR-FTIR microscopy requires long total sample measurement times because individual particles need to be placed into the system manually. There is also a high risk of sample contamination and loss.
- µFTIR in transmission mode may be unable to detect particles because of total absorption of the IR beam for thick particles.
- µFTIR in reflection mode is only suitable on surfaces with IR beam reflective properties, which limits its applicability for smaller or dark-colored particles.

With decreasing particle size samples, handling becomes increasingly difficult. To avoid sample loss, all particles of interest are concentrated onto membrane filters, reflective slides, or IR transparent slides and windows. Various types of membrane filters like metal-covered PC filters (Cabernard et al., 2018) and silicon membranes are used (Käppler et al., 2015, 2016), but aluminum oxide filters are the most widely applied (Löder et al., 2015; Primpke et al., 2020a).

Despite the characterization power of FTIR spectroscopy approaches, some limitations remain. Determining the location of potential particles on the filters/slides can be challenging, although different methodologies are available, starting with the preselection of particles by visual identification (Cincinelli et al., 2017; Phuong et al., 2018), selection and counting by particle finders (Palatinus et al., 2019; Renner et al., 2019c; Brandt et al., 2020), or the complete spectroscopic imaging of the filter area (Löder et al., 2015; Tagg et al., 2015). Furthermore, no particles on the filter/slide should overlap to avoid sequestration and misidentification of particle sizes and numbers. For these reasons, combined with the high number of particles in some samples, often only a fraction of the total extracted sample can be investigated within one measurement (Cabernard et al., 2018). Additionally, large numbers of particles increase measurement times. Staining methods for a pre-screening are reasonable and seem not to influence the IR-based analysis.

µFTIR via hyperspectral imaging

To avoid staining or to achieve defined measurement times per sample in routines, chemical imaging (µFTIR) is the method of choice. All particles are analyzed, even if they form particle clusters. In principle, imaging can be performed by any FTIR microscope equipped with single element mercury cadmium telluride (MCT) detectors, but measurement times increase significantly with imaged filter area (Harrison et al., 2012; Vianello et al., 2013). These limitations are reduced by hyperspectral imaging via focal plane array (FPA) detectors, which currently can collect up to 128 x 128 spectra/pixels within a single scan (Löder et al., 2015; Tagg et al., 2015). These systems currently represent the state of the art in MP analysis because they allow fast, effective identification and quantification of MP, as demonstrated for different ecosystems and waste management systems (Primpke et al., 2020a). This type of analysis generates large numbers of spectra (e.g., 1.5 to 3 million), which can be analyzed with the help of false color images or semi-automated data analysis (Primpke et al., 2020a). To overcome limitations by manufacturers and differing databases for library searches, open source software tools are available, which have the additional advantage of harmonizing MP analysis (Primpke et al., 2020a, b).

Raman spectroscopy for microplastic analysis

The analysis of MP via Raman spectroscopy allows measurement of particles down to 1 µm in size. Although Raman spectroscopy is typically considered non-destructive, the method uses a focused laser beam that may cause damage to the analyzed particles, which increases in severity with the speed of analysis because more energy is focused on the same small area. Measurements are performed on the particle surface due to inelastic laser light scattering; photons interact with molecules, which either absorb or lose energy during this process. The obtained vibrational spectra are complementary to FTIR because of different selection rules for this process. Similar to the interpretation of the FTIR spectra, the chemical/polymer identification is performed by library searches. Most Raman spectrometers are connected to microscopes, which increases the spatial resolution and allows the determination of particle numbers, shape, size, and polymer type within a single measurement (Cabernard et al., 2018).

Similar to FTIR, larger particles (> 500-300 µm) can be isolated prior to filtration and targeted as single particles. The measurement of single particles is often performed on highly reflective surfaces to avoid background signals from the support materials. Highly recommended for this application are metal-coated mirrors, aluminum sheets, or coated slides (Oßmann et al., 2017). Similar approaches can also be used for automated particle identification on filter membranes (Frère et al., 2016), especially for smaller MP (< 20 µm). The filters are commonly metal-coated PC membranes (Oßmann et al., 2017, 2018; Araujo et al., 2018; Cabernard et al., 2018; Schymanski et al., 2018) or silicon membranes (Käppler et al., 2015, 2016). Raman spectroscopy is one of the few methods to characterize particles successfully down to 1 µm (Oßmann et al., 2018) in simple matrices like drinking water, while in more complex sample matrices identification of particles > 5 µm has been demonstrated (Imhof et al., 2016; Käppler et al., 2016; Cabernard et al., 2018; Oßmann et al., 2018; Schymanski et al., 2018). Furthermore, it has been proposed that the technique might be able to measure particles in the nanoplastics size range (< 1 µm; Schwaferts et al., 2019). Raman spectroscopy has the advantage that each particle will be documented by shape and size, which allows for immediate calculation of particle numbers, as well as size and shape distributions. These processes can be automatized using a particle-finder mechanism to determine particle shape, size, and polymer type, which helps to reduce both researcher bias and measurement time (Frère et al., 2016; Cabernard et al., 2018). Or, the entire filter area can be measured by the imaging system.

However, this approach still has long measurement times. Measurement times differ highly between studies from just a few seconds to almost an hour for single particles (Primpke et al., 2020a). Sample analysis times range from several days to weeks for small MP (< 10 µm) because they typically occur in high particle numbers (> 1000 particles per filter; Primpke et al., 2020a). To circumvent such long measurement times, sometimes only partial analysis of the filter membranes (0.1–30% of the area) is performed (Cabernard et al., 2018; Oßmann et al., 2018; Schymanski et al., 2018). However, a controlled method for ensuring representative analysis of sample subfractions is currently lacking.

Compared to targeted particle analyses assisted by particle finders, imaging the whole filter area allows the identification and characterization of more particles in the same sample (Käppler et al., 2016; Araujo et al., 2018), similar to FTIR imaging. However, the measurement times required for Raman imaging are significantly longer than those required by FTIR imaging. For example, an area of 1 mm^2 had a scanning time of 38 h for a measurement at 10 µm resolution (Käppler et al., 2016). This is considerably longer than for FTIR, which is capable of comparable imaging within minutes. A promising approach for faster measurements by stimulated Raman scattering (Zada et al., 2018) decreases the time significantly but is limited to particles in 12 µm resolution and is only suitable for a few polymer types. On the positive side, compared to FTIR, in Raman spectroscopy plenty of parameters can be adjusted to improve the signal to noise ratio, including spectral range, excitation wavelength, the applied objective, resolution, and the number of accumulations.

In conclusion, for routine bulk sample analysis, Raman is much slower than FTIR microscopy. However, Raman has the capability to identify niche polymers and smaller size classes, if time plays a subordinated role.

Thermoanalytical methods combined with gas chromatography and mass spectrometry

Thermal degradation methods of various modifications and combinations are versatile analytical techniques that have a long tradition in the field of polymer producing and processing industry, as well as polymer analysis (Wampler, 2006; Tsuge et al., 2011; Kusch, 2012, 2014; Kusch et al., 2013). A comprehensive collection of pyrolytic data for polymers (more than 165) is given by Tsuge et al. 2011. Although thermal methods are destructive, they can be preceded by optical chemical identification such as FTIR or Raman where required.

For these MP identification methods, polymers are broken down into polymer-specific degradation products at elevated temperatures and under exclusion of oxygen. Volatile components are separated on a gas chromatographic (GC) column, allowing for rough analysis. Additional coupling to a mass spectrometer (MS) enables the specific identification of all generated compounds and the potential for quantification.

The most established techniques for the systematic decomposition of polymers are online pyrolyzers coupled with gas chromatography mass spectrometry (py-GC/MS) and thermogravimetric analyzers (TGA) combined with evolved gas analysis (EGA). The latter can be performed with different types of detection systems. There are three common types of pyrolyzers (Wampler, 2007), which differ in terms of temperature generation and mode of operation, heat transfer, and available sample targets crucial for sample capacity:

- Filament pyrolysis can operate isothermally or with a temperature program. It typically uses open or semi-closed quartz tubes that are placed in a heated platinum coil (Fries et al., 2013; Dekiff et al., 2014; Nuelle et al., 2014).
- (Micro)furnace pyrolysis can operate isothermally or with a temperature program. The samples are transferred into stainless steel cups that are heated in a ceramic oven (ter Halle et al., 2016; Hermabessiere et al., 2018; Käppler et al., 2018; Fischer and Scholz-Böttcher, 2019; Gomiero et al., 2019).
- Curie point (CP) pyrolyzers perform exclusively isothermally. They use wires or semi-closed ferromagnetic targets. Their alloy defines a discrete, exact pyrolytic temperature that is almost instantaneously reached when placed in a high-frequency coil chamber. Alloys are available for a broad temperature range (Fischer and Scholz-Böttcher, 2017).

The theoretical sample capacity of the targets ranges between 1.5 mg (CP) to 50 mg (micro furnace). Realistic sample volumes are around 1 mg or less for optimal operating conditions. Filament systems (temperature programmed heating) and micro furnace pyrolyzers (double shot option) enable a stepwise analysis of samples in which low molecular organic additives, monomers, and accumulated smaller organic contaminants can be desorbed from the sample in a first moderate heating program (ideally combined with a cryo-focusing unit) before pyrolysis is performed under polymer decomposition conditions. This type of sample processing makes valuable, additional information accessible.

In TGA, a polymer decomposes during a controlled heating process, in which the weight of the polymer changes in a characteristic way and can be recorded as a function of temperature. The generated decomposition gases can be analyzed and used for polymer identification (Tsuge et al., 2011; Seefeldt et al., 2013). A special form of TGA is the recently introduced TED (thermo extraction desorption)-GC/MS (Dümichen et al., 2015, 2017, 2019). The decomposition gases are adsorbed and concentrated on a solid phase absorber bar and subsequently desorbed and transferred into a GC/MS. The sample capacity in TED-GC/MS is stated as 100 mg.

Thermal polymer identification combined with GC/MS coupling

For MP identification in complex environmental samples, the high compound resolution power of GC/MS coupling offers higher analytical potential compared to pure EGA techniques. Irrespective of the pyrolytic system, all thermal methods working with a GC/MS coupling rely on the same principle of polymer identification. Polymeric compounds degrade under the exclusion of oxygen and defined temperature conditions into several products, characteristic of different polymer types. The volatile components undergo GC separation prior to identification by MS. The resulting characteristic pyrogram acts as a fingerprint for identifying the polymer types (Figure 4.4). The MS analysis provides a detailed chemical characterization of the respective products when this is required. To generate a diagnostic pyrogram, a minimum of 1-10 µg polymers are typically necessary, although individual particles with a mass of 0.3 µg isolated from a sediment sample have been successfully identified (Käppler et al., 2018).

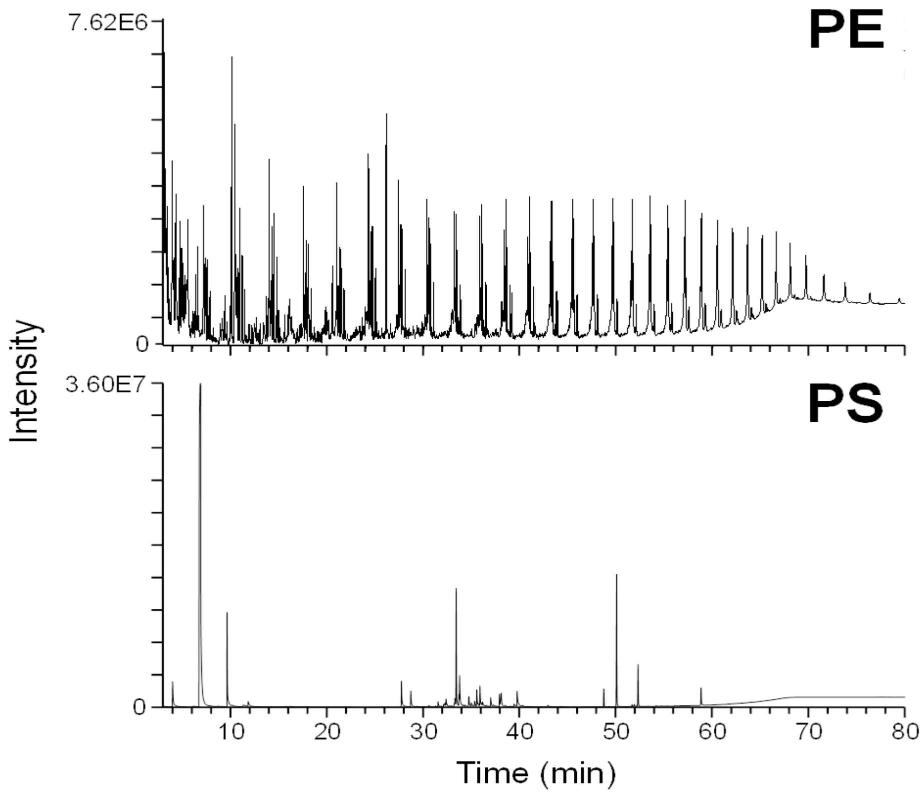


Figure 4.4 Example “fingerprint” pyrograms (total ion current chromatograms, py-GC/MS coupling) of an isolated PE (52 µg) and PS (20 µg) particle, respectively. Source: Scholz-Böttcher, unpublished.

Specific pyrolysis products and combinations of pyrolysis products are characteristic for a given polymer, meaning good chromatographic separation allows simultaneous detection and identification of multiple polymers when present as a mixture. For this purpose, the retention time data of characteristic polymer degradation products and characteristic indicator ion(s) from their respective mass spectra are extracted in an ion chromatogram, representative for each polymer. Py-GC/MS has been applied successfully for the simultaneous detection of up to 10 different polymers in various complex matrices (Fischer and Scholz-Böttcher, 2017, 2019; Gomiero et al., 2020; Primpke et al., 2020c). Equally, the application of TED-GC/MS has successfully identified synthetic polymers in complex environmental samples (Dümichen et al., 2015, 2017; Eisentraut et al., 2018).

The limits of detection (LOD) range at the nanogram level are polymer- and indicator ion-dependent and closely related to the sensitivity of the GC/MS system (Fischer and Scholz-Böttcher, 2019). To avoid high background signals masking the target analyte signals and efficiently reducing sample volume, the application of py-GC/MS to environmental samples requires an adequate pre-treatment to remove and reduce accompanying inorganic and organic matrices (Fischer and Scholz-Böttcher, 2017, 2019; Gomiero et al., 2020). For application on environmental samples, MP extracts are concentrated on glass fiber or ceramic (e.g., anodisc) filters (Fischer and Scholz-Böttcher, 2017, 2019; Gomiero et al., 2019; Primpke et al., 2020c). The derivatization agent tetramethylammonium hydroxide (TMAH) has been successfully used to increase the detection sensitivity of MP by py-GC/MS (Challinor, 2001; Fischer and Scholz-Böttcher, 2017).

Thermal polymer quantification combined with GC/MS coupling

Using external calibration, integration of the selected indicator ion(s) leads to the corresponding mass of the respective polymer in a given sample. This mass reflects the “bulk” concentration of the respective polymer in the sample because py-GC/MS does not distinguish, e.g., between pure polymer, co-polymer, or other admixtures (cf. Fischer and Scholz-Böttcher, 2017, 2019). The resulting mass-related data are independent from any kind of particle properties such as shape, size, density, texture, surface aberrations, color, brightness, opacity, or weathering. Microplastics quantification requires an adequate digestion cleanup step to ensure subsequent chromatographic performance and data quality, especially with an increasing content of non-plastic organic material (OM) in a sample (Fischer and Scholz-Böttcher, 2019).

In TED-GC/MS, only the trapped gaseous products of the pyrolyzed sample (via TGA) are analyzed via GC-MS after subsequent thermal desorption. Thermogravimetric analyzer sampling cups enable a direct sample measurement for MP if its content exceeds 0.4% w/w (Dümichen et al., 2015, 2017; Eisentraut et al., 2018). A high organic content in the sample matrix can perturb the analytical performance. With TED-GC/MS, the opportunity to reduce OM a certain extent by sequential heating and discarding products generated below specific temperatures is offered (e.g., 350 °C). Although this can eliminate products that originate from more thermolabile natural OM, it also risks the loss of more thermolabile polymers (e.g., PVC).

The limits of quantification (LOQ) have been identified as being below 1 µg (Fischer and Scholz-Böttcher, 2019). However, LOQs are determined more by the GC/MS-system than by the pyrolysis method employed. Usually, the MP content of environmental samples is in the ppm range and below (Fischer and Scholz-Böttcher, 2019), making preconcentration of the extract prior to analysis indispensable. Lower detection and quantification limits combined with higher substance selectivity may be reached by using triple quadrupole GC/MS or by coupling of the py-GC system to a high-resolution MS with an Orbitrap. Although thermal methods are destructive, retrospective data analysis for indicator compounds of further polymers is possible from stored data files if analysis is performed in full scan mode. Besides the opportunity for an additional polymer identification, the use of internal pyrolysis process standards (ISTDpy) enables a retrospective and at least the semi-quantification of these polymers.

Synergies between thermal degradation and spectroscopic methods

The thermal degradation-based detection methods and spectroscopic methods produce complementary data (Hendrickson et al., 2018; Käppler et al., 2018; Primpke et al., 2020c). Thermal degradation methods provide the mass of the polymer independent of its appearance in the sample, whereas FTIR and Raman methods provide particle size and number information. Currently, there are few pathways to convert the data measured via FTIR to mass-related data (Simon et al., 2018; Mintenig et al., 2020), but these methods are currently heavily limited if larger particles are present in greater numbers because the particle shapes are currently mainly based on ellipsoid particle shapes (Primpke et al., 2020c). Therefore, better solutions for the conversion between the datasets still need to be developed.

Upcoming methods and technologies

Currently, several other techniques are being tested for the investigation of MP including flow cytometry, hyperspectral imaging, and size-exclusion chromatography (Primpke et al., 2020a). Most of these techniques are still in an evaluation phase and will be reassessed in future updates of the guidelines. Nevertheless, recent developments allow the rapid mapping of large filter areas using quantum-cascade laser imaging system: these are currently under investigation for their application in MP research (see Figure 4.5) allowing measurement down to 36 minutes per sample on a 12 × 12 mm² area (Primpke et al., 2020d).

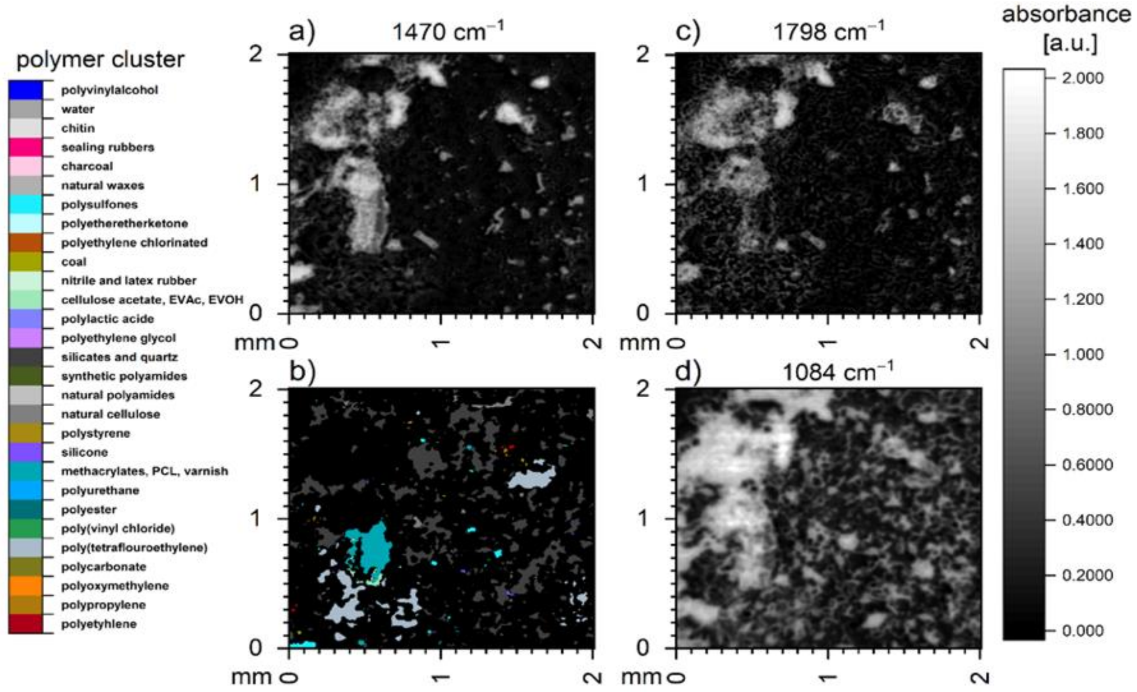


Figure 4.5 The application of quantum cascade laser-based imaging on a sediment sample showing 1 of the 36 measurement fields with absorbance features at various wave numbers (a, c, d) as well as the identified polymer types (b).

4.3.4 Outlook: promising methods for small plastic particle (< 10 µm) quantification

Many studies on physiological effects use pristine spherical, either heavily colored or fluorescent-labeled MP. This allows for the traceability of such particles in the body, using microscopy down to the micro- or nanoscale (Huffer et al., 2017). However, in the environment, MP are not pre-labeled. Therefore, chemical identification is necessary. Chemical imaging methods for MP have lower detection limits for single particles compared to fluorescent imaging, ranging between below 1 µm for Raman technologies and up to 20 µm for some FTIR technologies (Huffer et al., 2017). The best FTIR microscopes have a particle-size detection limit in the low µm range (2.5–5 µm). However, practically applied and published limits so far seem to be around 10 µm for µFTIR imaging (Mintenig et al., 2017, 2019; Primpke et al., 2017; Simon et al., 2018). Raman microscopy comes with the drawback of being slow. Because of the energy applied to the particle, increasing speed destroys the plastic. This problem can be circumvented by a flow-through technique, immersing each particle in a focused stream of water (S. Gallager, Woods Hole Oceanographic Institute, MA, USA, *personal communication*). Additionally, Raman output is often hampered by increased fluorescence (Elert et al., 2017). However, promising approaches might overcome this problem by Time Domain Raman Spectroscopy (S. Gallager, *personal communication*). With these techniques, a chemical identification can be combined with an overview of the particle-size distribution down to the small µm size range. The investigation of physiological effects associated with the smaller micro- and nanoplastic particles, including reliable risk assessments, may be improved by the application of nuclear isotope techniques to investigate consequences associated with plastic particles including their accumulation, translocation, and trophic transfer (Lanctôt et al., 2018). Such methods might allow the tracing of particles without prior tagging.

Conclusions

Most discussed methods necessitate a comprehensive extraction of MP from the sample. Procedures are difficult and time consuming, and particles are lost in the procedure, increasingly so with decreasing particle size. There are quantification approaches circumventing extraction, chemometric approaches combined with mass spectrometry, and thermal extraction desorption gas chromatography mass spectrometry (TED-GC/MS). These apply an array of gravimetry, passive sampling of the evaporate, and chemical characterization, which may help with the identification in a complex substance (Dümichen et al., 2017), but this analytical approach is not suitable for environmental samples in which typically low concentrations of MP meet an excess of complex inorganic and organic natural matrices. Here, high detection sensitivity and reliability are requested by the research community/legislation bodies from the instrument and protocol developers, and any matrix interferences should be excluded. In particular, regarding thermal methods, high-organic matrix loads might lead to severe interferences. Overall, the accompanying matrix determines the extraction effort before any specific MP analysis. The detection limits in terms of mass/sample mass are relatively large, rendering the method unsuited for food safety approaches, but potentially valuable for samples very low in accompanying organic material.

4.3.5 Guidelines for the identification of microplastics

Considerations regarding the costs of the analysis

The analysis of MP can be assumed to be expensive either because of instrument costs or personnel demands. In a recent study, such factors were assigned to the different techniques (see Table 4.2).

Table 4.2 Cost estimation for the presented analytical techniques ranging from optical methods toward chemical analysis. Reproduced from Primpke et al., 2020a.

Methods	Unit	Naked eye	Optical microscopy	Nile red staining	FTIR qualitative	Particle based µFTIR	µFTIR imaging	Raman qualitative	Particle based µRaman	Py-GC/MS qualitative	Quantitative Py-GC/MS	TED-GC/MS
LOD		1 mm	100 µm	3-20 µm	> 300 µm	25 µm	10 µm	> 300 µm	1 µm	~1 µg IP	<< 1 µg PD	< 1 µg PD
Instrument costs[a]	$k	< 1	2-3	2-50	25-50	100-125	200-250	50-100	200-400	> 150	> 215	>250
Special consumables				Dye and solvent		Liquid nitrogen	Liquid nitrogen			GC- Columns and filaments	GC- Columns and filaments	GC- Columns and filaments
Field applicability		Good	Good	No	Handheld	No	No	Handheld	No	No	No	No
Limitations		NoID	NoID, NoM, PA/SA	NoID, NoM, PA/SA		TA, NoM	TA, NoM		PA/SA NoM		NoN, NoS	NoN, NoS
Automated data evaluation		No	No	No*	No	Yes	Yes	Yes**	Yes	No	No***	No***
Measurement time[b]	min	1	60	35	1	360	240	2	2580 - > 10000	35-120	120	120
Data analysis time[b]	min	NA			1	60	360	1	1	5-10	60****	60****
Working time[b]	min	1	60	35	2	120	60	3	60 - 580	5	30 (qual.) 72 (quant.)****	30 (qual.) 72 (quant.)****
Typical fractions per sample		50 P	7 F	7 F	50 P	1 F	1 F	50 P	1 F	50 P	1-5 CQ	1- 5 CQ
Instrument availability for analysis[c]	d	261	261	261	250	250-261	250-261	250-261	250-261	250	250	250
Average working time per sample	min	PND	420	245	PND	120	60	PND	60	PND	72-216	72-216
Field of application		MD, MO	MD, MO, R	MD, MO, R	MD, MO, R, RA, RE	MD, MO, R, RA, RE	MD, MO, R, RA, RE	MD, MO, R, RA, RE,	MD, MO, R, RA, RE	MD, MO, RE,	MD, MO, R, RE	MD, MO, R, RE

[a]Raw estimates may strongly vary, depending on the country. [b] Calculated for one filter/particle per analysis. [c]Working days (normal work hours/days, maximal 261 if a 2-day weekend applies) exclusive instrument maintenance time.
Note: CQ: pyrolysis cubs or quartz tubes; F: filters; IP: isolated particle; LOD: limits of detection; LID: limited chemical identification; MO: monitoring; MD: modeling; NoID: no chemical identification; NoM: no mass determination; NoN: no particle number determination; NA: no information available; NoS: no particle sizes determination; R: routine; RA: risk assessment; RE: research; PA/SA: partial analysis/subsampling analysis on filter; P: particle; PD: polymer dependent; PND: particle number dependent; REP: replicates; TA: total absorption. image analysis possible, ** for Raman microscopes, *** autosamplers are available, **** calculated based on a micro-furnace system with an average sequence size (6 standards, 10 samples).*

Although optical microscopy is inexpensive from an instrumental point of view and can be easier to use in the field or on a research vessel, the personnel demand is rather high because of the number of potential samples to be analyzed. Futhermore, optical microscopy is prone to a human bias and dependent on the application of strict and harmonized identification guidelines. Chemical identification by microscopy-spectroscopy, on the other hand, is rather expensive from the instrumental side, but the personnel costs are lower; the net analysis time is approximately 1-2 hours per sample compared to 4-7 hours using optical microscopy (even supported by dye staining). In the case of monitoring in the Arctic, a good compromise between chemical accuracy, field work applicability, and costs needs to be defined. From the Monitoring Guidelines, the following individual needs were derived (see Table 4.3).

Table 4.3 Summary of the demanded data accuracy for monitoring in the individual compartments for the different size classes.

Matrix	**Number**	**Mass**	**Size**	**Subsampling recommended**	**Size and shape**	**Color**	**Chem-ID**
Air	Mandatory	-	< 300 µm	No*	Mandatory	-	Yes
Water	Mandatory	-	5000 - 300 µm	For Chem-ID	Nice to have	Nice to have	Yes (1 mm - 300 µm) **
Water	Mandatory	-	< 300 µm down to LOD	Nice to have	Nice to have	Nice to have	Nice to have
Sediments	Mandatory	Nice to have	5000 - 300	For Chem-ID	Mandatory	mandatory	Yes (1 mm - 300 µm) **
Sediments	Nice to have	Nice to have	300 - down to LOD	For Chem-ID	Mandatory	mandatory	Nice to have
Ice	x	Nice to have	5000 - 300	-	Mandatory	mandatory	Yes (1 mm - 300 µm) **
Ice	Nice to have	Nice to have	300 - down to LOD	-	Nice to have	Nice to have	Nice to have
Shorelines***	Mandatory		> 25 mm	Not defined	Not defined	Not defined	Not defined
Soils	Mandatory	-	5000 - 300 µm	Yes	Yes	Yes	Nice to have
Biota	Mandatory	-	> 100 µm	For Chem-ID?	Mandatory	Nice to have	Yes
Fish	Mandatory	Mandatory	> 500 µm	For Chem-ID	Size mandatory, shape beneficial to have	Nice to have	Yes (1 mm - 500 µm) **
Fish	Beneficial	Beneficial	< 500 µm	For Chem-ID	Size beneficial to have/to be developed, shape beneficial to have	Nice to have	Yes (1 mm - 500 µm) **
Bird	Mandatory	Mandatory	5000 - >300 µm	For Chem-ID	Nice to have	Nice to have	Yes (1 mm - 300 µm) **
Mammal	Mandatory	Mandatory	> 2.5 cm - 300 µm	For Chem-ID	Size mandatory, shape Nice to have	Nice to have	Yes (1 mm - 300 µm) **
Mammal	Nice to have	Nice to have	< 300 µm to LOD	For Chem-ID	Nice to have	Nice to have	Nice to have

*Subsampling should be avoided, ** Analysis of at least a subsample, *** No MP define.

Implications for reporting on microplastics

A diverse range of methods and non-standardized approaches have been developed and implemented by researchers for reporting MP sample collection, extraction, and analysis, along with a range of data reporting formats. These methods are often insufficiently described or exhibit key differences that result in many studies being neither comparable nor reproducible. Each method has its strengths and weaknesses, and there are continued efforts to optimize existing methods and develop new ones that may improve throughput, detection limit, and reproducibility. Trying to find optimized approaches has led to the rapid evolution of the methods applied in the last few years.

Unfortunately, one outcome has been the inability to answer larger-scale questions related to MP pollution. As this new research field evolves, it is striving to establish a harmonized community approach to developing, applying, and reporting methodologies. A recent publication has provided a comprehensive set of recommendations and guidelines for the reporting of MP data that aims to increase the reproducibility and comparability between studies (Cowger et al., 2020b). We recommend that the same methodological approaches and data reporting criteria are recommended in the AMAP Guidelines to help achieve harmonization across MP studies conducted by different research groups around the world.

Key goals for MP monitoring in the Arctic:

- Identifying and addressing key reproducibility and comparability problems and solutions for MP research;
- Identifying and prioritizing key methodological parameters;
- Implementing reporting guidelines for researchers to use when reporting, comparing, and developing methods.

Figure 4.6 shows the Mind Map produced by Cowger et al., 2020b in which general method groups flow from the primary term “Microplastics Reporting Guidelines.” These general groups are further refined by subgroups of method types and instrument groups in which the terminal node of every branch leads to essential methodology elements (italicized) that should be reported. Each reporting guideline is described by an explanation, reasons to report, and/or examples from published MP literature. The interactive Mind Map is available as an Open Science Framework project (OSF) in which users (including users of these AMAP Guidelines) can access more details.

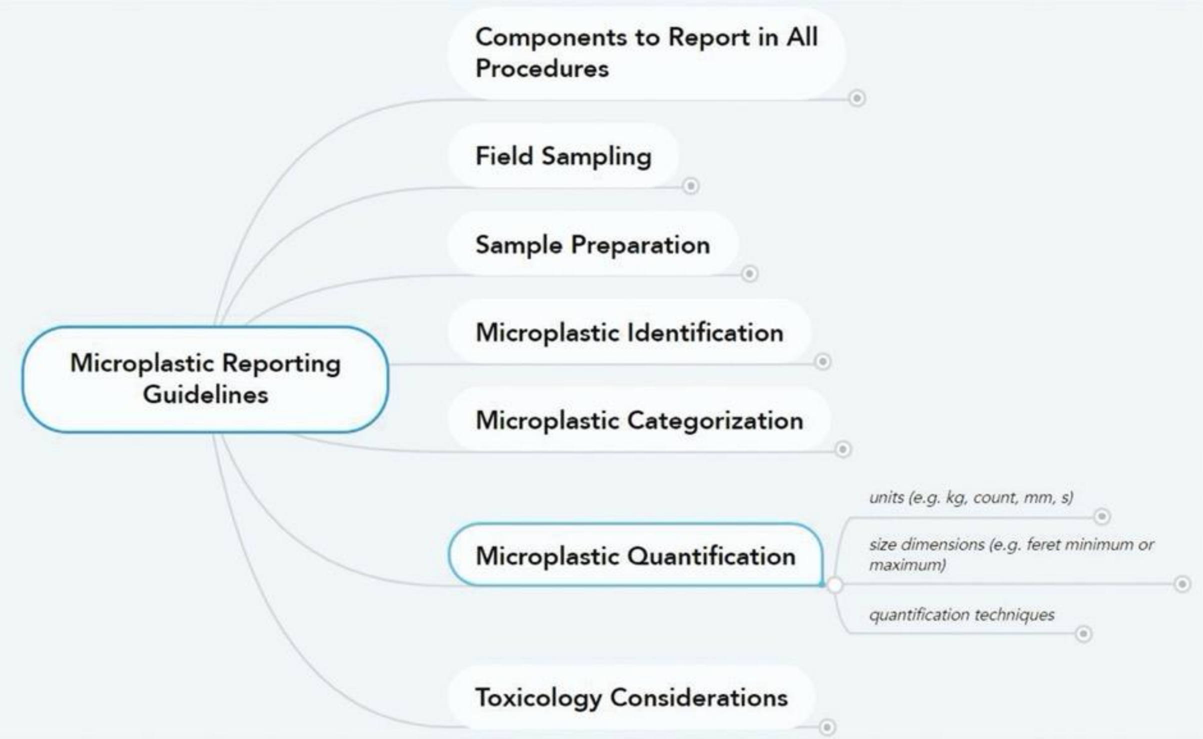


Figure 4.6 Mind Map showing the components and flow of reporting guidelines for microplastic studies. The first nodes, branching off "Microplastic Reporting Guidelines," are the general groups of the guidelines, subgroups follow in bold until the second to last nodes are the reporting guidelines (in italics), and the terminal node is the description of the guideline. Reproduced from Cowger et al. (2020b).

Tables 4.4 to 4.8 summarize the information and data reporting recommendations presented in the Cowger et al. (2020b) publication.

Table 4.4 Components to report in all procedures.

Parameter	Reporting requirements
Materials	● All manufacturers of materials and instruments and their calibration ● All software used and their calibration
Quality assurance/quality control	● Error propagation (how instrumental, methodological, and/or statistical error were propagated) ● Replicates (number of replicates; how replicates were nested within samples) ● Limit of detection (quantitative detection threshold; plastic morphology, size, color, and polymer limitations of method; method of accounting for non-detects) ● Procedural: blank controls (number of controls; characteristics of plastics found in blanks with the same rigor as samples; potential sources of contamination; point of entry and exit to method) ● Positive controls/recovery tests, ideally with the same particle quality as the analytes (morphology, size, color, and polymer type of positive controls; positive control correction procedure; point of entry and exit to method) ● Contamination mitigation (clothing policies; purification technique for reagents; glassware cleaning techniques; containment used (e.g., laminar flow cabinet/hoods, glove bags)
Data reporting	● Share raw data and analysis code as often as possible

Table 4.5 Field sampling procedures.

Parameter	**Reporting requirements**
Field sampling	● Where (e.g., region) and when (e.g., date, time) the sample was collected ● Size (e.g., m^3, kg) and composition (e.g., sediment, water, biota) of the sample ● Location at the site that sample was collected (e.g., 3 cm depth of surface sediment) ● Sample device dimensions and deployment procedures ● Environmental or infrastructure factors that may affect the interpretation of results ● How samples are stored and transported

Table 4.6 Sample preparation.

Parameter	**Reporting requirements**
Homogenization	● Homogenization technique
Splitting/subsetting	● Sample splitting/subsetting technique
Drying	● Sample drying temperature and time
Synthesized plastic	● Synthesized plastic polymer, molecular characteristics, size, color, texture, and shape ● Synthesized plastic synthesis technique
Fluorescent dye	● Dye type, concentration, and solvent used ● Dye application technique
Sieving strategy	● Sieve mesh size ● If the sample was wet or dry sieved
Density separation	● Concentration, density, and composition (e.g., CaCl2, ZnCl) of solution ● Time of separation ● Device used
Digestion	● Duration and temperature of digestion ● Digestion solution composition ● Ratio of digestion fluid to sample
Filtration	● Filter composition, porosity, diameter

Table 4.7 Microplastic identification

Parameter	Reporting requirements
Visual identification – imaging settings	• Imaging settings (e.g., contrast, gain, saturation, light intensity) • Magnification (e.g., scale bar, 50X objective)
Visual identification – light microscopy	• Magnification used during identification • Shapes, colors, textures, and reflectance used to differentiate plastic
Visual identification – fluorescence microscopy	• Magnification used during identification • Fluorescence light wavelength, intensity, and exposure time to light source • Threshold intensity used to identify plastic
Visual identification – scanning electron microscopy (SEM)	• Coating used (e.g., metal type, water vapor) • Magnification used during identification • Textures used to differentiate plastic
Chemical identification - pyrolysis gas chromatography mass spectrometry (py-GC/MS)	• Pyrolysis gas, temperature, duration • additional techniques (if performed), e.g., online thermochemolysis/pyrolytic derivatization • GC oven, program, temperature, carrier gas, and column characteristics • MS ionization voltage, mass range, scanning frequency, and source/analyzer temperature • Referred polymer specific indicator products, py-GC/MS matching criteria (i.e., match threshold, linear retention indices (LRI), and Kovats indices) • Py-GC/MS quantification techniques
Chemical identification - Raman spectroscopy	• Acquisition parameters (i.e., laser wavelength, hole diameter, spectral resolution, laser intensity, number of accumulations, time of spectral acquisition) • Pre-processing parameters (i.e., spike filter, smoothing, baseline correction, data transformation) • Spectral matching parameters (i.e., spectral library source, range of spectral wavelengths used to match, match threshold, matching procedure
Chemical identification - Fourier-transform infrared spectroscopy (FTIR)	• Acquisition parameters (i.e., mode of spectra collection, accessories, crystal type, background recording, spectral range, spectral resolution, number of scans) • Pre-processing parameters (i.e., Fourier-transformation (FT) parameters, smoothing, baseline correction, data transformation) • Matching parameters (i.e., FTIR spectral library source, match threshold, matching procedure, range of spectra used to match) • Differential scanning calorimetry (DSC) • Acquisition parameters (i.e., temperature, time, number of cycles) • Matching parameters (i.e., parameters assessed, reference library source, comparison technique)

Table 4.8 Categorization and quantification.

Parameter	Reporting requirements
Categorization	• Shape, size, texture, color, and polymer category definitions
Quantification	• Units (e.g., kg, count, mm) • Size dimensions (e.g., Feret minimum or maximum) • Quantification techniques

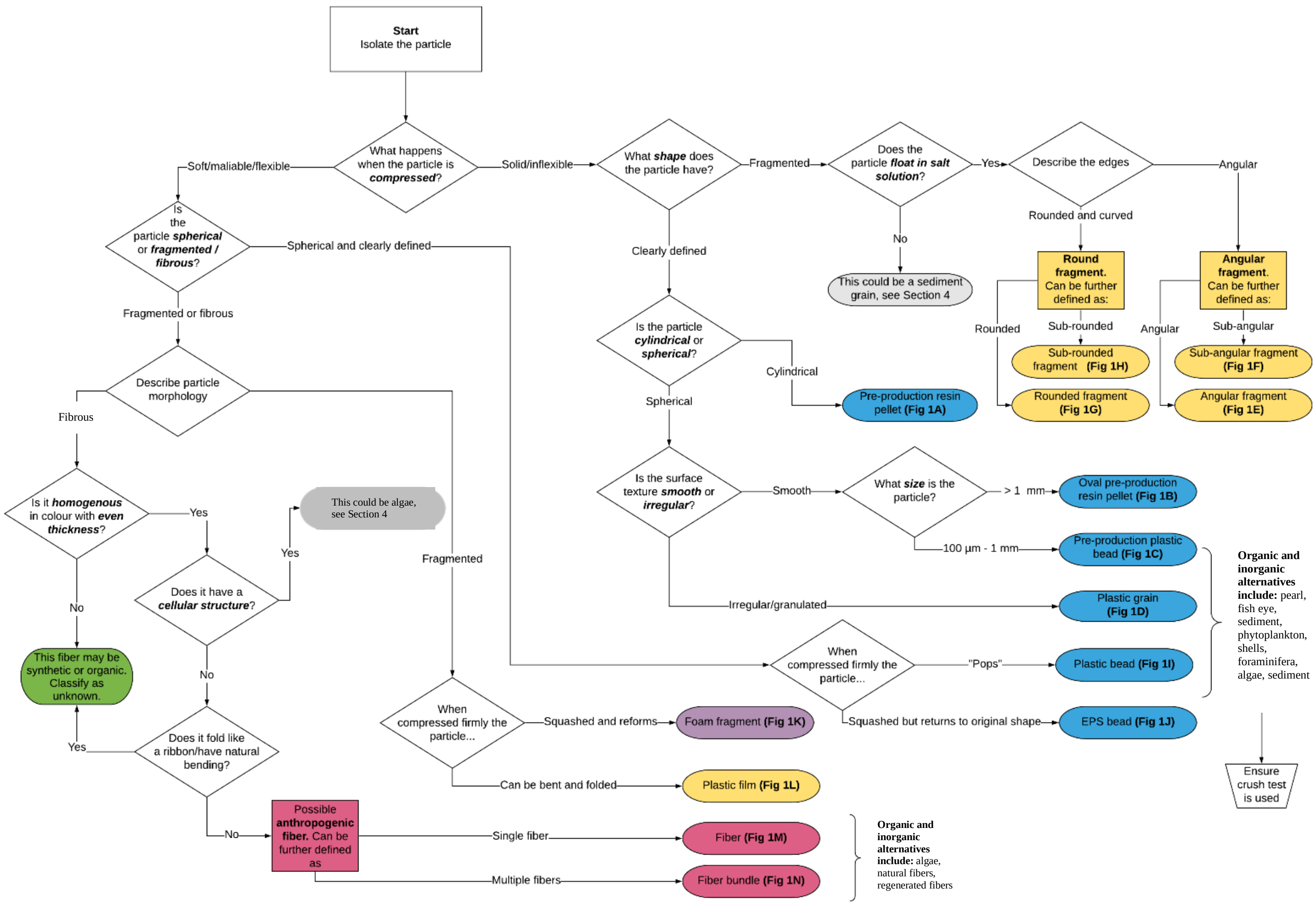
The generated data in the number of MP or mass of polymer/s should be stored with as much detailed information as possible for an individual research/monitoring campaign. This data should include all parameters of interest on a particle-based level, if applicable, and made available upon request for modeling and risk assessment studies.

Identification guidelines for monitoring microplastics in the Arctic

Because of the high variability across different analytical methods and tools, variations in field-work capabilities, and different targets for monitoring of individual biotic and abiotic compartments (see Table 4.3 and the related sections), we recommend the following procedure:

In the scope of the AMAP monitoring program, the data need to be harmonized for polymer types, size classes, colors, and shapes. For MP determination using optical microscopy and visual identification, it should be mandatory to follow the categorization scheme published by Lusher et al. 2020 (see Figure 4.7) to achieve a harmonized result on shapes.

Figure 4.7 Proposed flow chart for the visual identification of microplastics. Reproduced from Lusher et al., 2020.



In addition, the following eight colors should be reported along with these shapes in accordance with the EMODnet database (https://www.emodnet-bathymetry.eu/):

- BLACK/GRAY
- BLUE/GREEN
- BROWN/TAN
- WHITE/CREAM
- YELLOW
- ORANGE/PINK/RED
- TRANSPARENT
- MULTICOLOR

For polymer analysis using spectroscopy, it is recommended to subsample at least 50 particles per sample or 66% of the filter, as reported by Mintenig et al., 2020. With MP particle sizes between 1 mm to 300 µm, this analysis is considered mandatory for most compartments when monitoring in the Arctic. To achieve an optimal harmonization between the results, we recommend that if using FTIR or Raman for spectral analysis by library searches, that open access databases be used for spectral matching (see, e.g., Cabernard et al., 2018; Primpke et al., 2018, 2020b; Munno et al., 2020). We also recommend open access software, like siMPle or Open Specy (e.g., Cowger et al., 2020c; Primpke et al., 2020b) to allow for the best comparability of data. In addition to synthetic polymers, these databases contain natural materials to avoid confusion, e.g., between protein based natural polyamides and synthetic polyamide. Nevertheless, other chemometric methods can be applied as well (e.g., Renner et al., 2017, 2019b; Hufnagl et al., 2019; Kedzierski et al., 2019; da Silva et al., 2020), however, a library search should be considered a standard method because it commonly provides the software running the instruments for all manufacturers. Independent from the method used to identify the spectra, a quality assurance/quality control of the method should be performed and reported using positive controls, negative controls, and for harmonizing the analysis of existing reference data sets. The methods should also be checked for known interferences with materials of natural origin regularly (at least every three months) to avoid an overestimation of MP.

Using thermoanalytical methods, the prepared sample is usually pyrolyzed as a whole. Any aliquotation should be avoided unless the results of aliquots are added together in the end. The expected polymer concentrations of an environmental sample should ideally fall within the linear quantification range of the polymer. This range varies within instrumentation. For micro furnace py-GC/MS, calibrations typically range between 0.5 and 100 µg but might vary between different types of polymers. Well-considered adjustments of sample volume or mass are highly recommended before any preconcentration procedure. Because mass-related data for polymers are still rare, relevant publications and experts should be consulted. As a first general appraisal from already existing data, total MP mass concentrations of ocean water range on a ppt to ppb level (Fischer and Scholz-Böttcher, 2019; Dibke et al., 2020; Primpke et al., 2020c), marine sediments range on a ppb level (Fischer and Scholz-Böttcher, 2019; Gomiero et al., 2019; Primpke et al., 2020c), and biota range in the ppb to ppm levels (Fischer and Scholz-Böttcher, 2017; Gomiero et al., 2020).

The derived sizes shall be reported in the size classes: > 1 mm, 1 mm – 300 µm, < 300 µm – LOD for several polymer types (see Figure 4.7) where the analysis is mandatory. The LOD of the data should be reported separately. If a certain polymer type was not measured, a not applicable (N/A) notice instead of a 0 is mandatory.

Table 4.9 Polymer types for data reporting

Polymer type name	**Examples of materials included (detailed level)**
Polyethylene based	HDPE, LDPE, and copolymers with a major PE fraction
Polypropylene based	PP copolymers with a major PP fraction
Polystyrene based	PS copolymers with a major PS fraction
Polyamide based	All types of PA like the various nylons
Polyurethane based	All types of PUR
Polymeth (ester)acrylate based	All types of PM(ester)A
Polyester	PET, all other types of polyesters
ABS	ABS
Polycarbonate	PC
Rubbers, sealing	Other rubbers, like EPDM
Rubbers, automotive	TWP
Paint/varnish particles	If separate from PM(R)A
Ethylene-vinyl acetate	
Cellulose acetate and similar	
Nitrile rubbers	
Natural rubber derivatives	
PAN	
Polyfluorinated polymers	e.g., PTFE
Polychlorinated polymers	e.g., PVC, chlorinated PE, various chlorinated polymers
Silicone rubbers and coatings	
Other plastics	e.g., PEEK
Other rubbers	
Other microlitter materials	

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Sampling the shoreline in Svalbard.

4.4 Modeling

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4.4.1 Introduction

The redistribution and accumulation of marine litter and microplastics (MP) in the environment including in the Arctic, are affected by the general atmospheric and oceanic circulation patterns. Modeling the movement and fate of marine litter can help us to better understand, and eventually address, its presence and impacts. Modeling the flow of marine litter into the Arctic has the potential to help identify and quantify sources, whereas modeling the movement and fate of marine litter within the Arctic can help identify geographic areas and marine litter types. That being said, modeling litter and MP in the Arctic comes with specific challenges.

Ocean general circulation models (OGCMs) solve equations to model ocean movement in horizontal and vertical dimensions and provide the surface currents layer that is used as the basic framework to simulate debris transport.

The models work best when initialized with actual data on starting conditions for debris quantity, concentration, and behavior. Observed data on litter and MP are negligible if compared to the immensity of the ocean, but even more scant if we consider oceanographic data from remote and harsh environments like the Arctic. Given the sparsity of observations, numerical simulations can be used to both fill in the gaps between these observations and to test hypotheses about how plastic particles behave in the ocean (van Sebille et al., 2020), especially when improved by satellite-tracked drifters (Maximenko et al., 2012) or with data assimilation techniques (Anderson et. al, 1996). Circulation models exist for the Arctic although generally at lower resolution, and there is continued effort to develop higher resolution circulation models in the region, such as those developed for the European Arctic by the EU project FixO3 with Frontiers in Arctic Marine Monitoring (FRAM; http://www.fixo3.eu/observatory/fram/).

One notable challenge for modeling marine litter in the Arctic is the presence of sea ice, 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, 2018; Tekmann, 2020). Modeling for these processes began several decades ago, particularly to study the redistribution of various pollutants and contaminants in polar regions (Pfirman et al., 1997; Rigor and Colony, 1997; Korsnes et al., 2002). However, plastic litter is a different contaminant because it has so many different properties in terms of size, shapes, and buoyancy, and thus it is much more difficult to use previous applications (van Sebille et al., 2020).

Given the large nature of plastic litter, the emphasis to date has been on oceanic modeling of plastic pollution. More recently, studies have shown that airborne plastic pollution can occur. This airborne deposition has mostly been studied in cities to date, including cities in Iran (Abbasi et al., 2019), Europe (Allen et al., 2019; Dris et al., 2015, 2016, 2017; Catarino et al., 2018; Klein and Fischer, 2019; Vianello et al., 2019), China (Cai et al., 2017; Liu et al., 2019), and over the Pacific Ocean (Liu et al., 2019b). Recent studies in remote regions, including the Arctic, suggest that atmospheric deposition of MP, especially fibers, can occur outside of major urban centers, with MP likely from remote sources (Ambrosini et al., 2019; Bergmann et al., 2019; Geilfus et al., 2019; Evangeliou et al., 2020). Integration of modeling for airborne input of MP is an area of future development because there are technical challenges in coupling air and ocean models, as well as data limitations in the quantification of MP input spatially and temporally.

4.4.2 Efforts to date

The majority of modeling work on marine litter movement and pathways has been done outside the Arctic. Recently, the various processes that govern the movement of plastic litter in the global ocean were summarized in a review by van Sebille et al., 2020. Advection of plastic litter into the Arctic Ocean by the pathway of the thermohaline circulation was modeled by Cózar et al., 2017. In the sub-Arctic and Arctic Regions, modeling to date involves the backtracking of litter from OSPAR beaches (Röhrs et al., 2020). Two- and three-dimensional simulations of particle transport trajectories have been used to identify different pathways for various polymer types (Tekmann et al., 2020). By applying a 1-D thermodynamic model with the backtracking of the sea-ice floes, it was possible to elucidate the incorporation of various polymer types during the sea-ice growth (Peeken et al., 2018). Although efforts using Lagrangian techniques to model the accumulation zones in sea ice and the ocean suggest no real accumulation of plastic litter in the high Arctic (Vries, 2019), by applying the Nucleus for European Modelling of the Ocean (NEMO), Mountford and Morales Maqueda, 2021 did show a projected increasing accumulation over time on the scale of several decades. In addition, they were able to show that, in regions of winter convection, floating plastic can be drawn down significantly through mixing and downwelling processes. For any sea-ice monitoring, basic model approaches such as sea-ice backtracking (Krumpen et al., 2016) are essential to determine the sea-ice origin and thus find the source of the plastic pollution.

Emerging broad-area modeling efforts, such as those through Tracking of Plastics in Our Seas (TOPIOS; http://topios.org/) would allow for improved investigation and assessment of marine litter into the Arctic via the marine environment. However, currently this is not the primary focus of this initiative. Additionally, there are no large-scale modeling efforts for atmospheric deposition of MP; in part because there are very limited data on how MP act within the atmosphere, and on how those would couple with modeling for oceanic transport of MP.

4.4.3 Difficulties or challenges

Oceanic modeling

Currently, the coupling between air and water is generally well understood, however, when adding ice to the modeling efforts several new scenarios arise. It is likely that proposed modeling approaches for marine litter in the Arctic would focus first on modeling the particular environmental conditions for the Arctic Ocean (e.g., large freshwater input) without sea ice, and later adapt them to the Arctic including the added complexity of sea ice. Additional modeling of sea-ice movement could assume debris entrapped or entrained within the ice. Modeling the debris/litter interactions during freeze-up will likely be very challenging. The complex rheology of ice (which behaves as a viscous liquid under one condition and as a rigid body under other conditions) makes this task even more difficult. Thus, one of the key challenges identified is the ability to include the influence of sea ice in the modeling of marine litter. As mentioned, this challenge exists at multiple levels: litter can become frozen into the sea ice and be transported, but it can also remain un-entrained and be degraded mechanically by sea ice and sea-ice biota

(Dawson et al., 2018). Entrainment processes are quite complex and demand very small-scale processes, which need to be interlinked with large-scale processes such as main oceanic currents and atmospheric forcing. Additionally, debris movement or transport may be influenced by sea-ice impact on ocean conditions, by freshening of the ocean surface layer, and by producing strong density gradients. This is in combination with the influence of large riverine inputs that already produce a fresher surface ocean compared to the world ocean.

Freshwater modeling

There is also a lack of modeling for freshwater inputs of litter and MP into the Arctic region. Freshwater inputs of litter and MP to the Arctic remain unknown, and pathways for litter and MP from oceanic and freshwater sources are needed to ensure mitigation efforts can be focused and effective. River systems have been identified as one of the key conduits of plastics from terrestrial environments to the world's oceans, transporting between 1.15 and 2.41 million tons of plastic annually to marine ecosystems (Lebreton et al., 2017), but similarly to the oceanic case, these modeling efforts are limited to lower latitudes. Although rivers are undoubtedly one of the major pathways in moving plastic from terrestrial to marine environments, little data are available on MP concentrations in northern rivers (or in freshwater ecosystems in general), and on how these systems may be acting as conduits for MP pollution to northern marine environments. Therefore, to add to our understanding of freshwater sources, sinks, and circulation of litter and MP, projects that focus on monitoring within watersheds and water bodies that flow into the Arctic should be prioritized.

Atmospheric modeling

As the study of MP in the atmosphere expands, there will be increased efforts to model MP movement and behavior in this environmental compartment. This will be an important component of understanding the flux of MP potentially into and out of the Arctic. Importantly, many chemical contaminants travel to the Arctic and become trapped there because of the "grasshopper effect." This phenomenon may, or may not, apply to MP, or apply differentially depending on polymer, size, and shape of the MP. Given the diverse nature of MP, more work is needed to understand the basic behavior of MP in air currents before large-scale modeling can take place.

4.4.4 Data needed and data gaps

Different approaches, and consequently different source data, are needed to model the general circulation and associated transport of litter and MP in the ocean and air. Because modeling techniques make use of a wide range of supporting elements, we recall here some major data sources used for modeling: drifters, satellite data, and oceanographic time series from fixed platforms.

Drifters

Drifter data are assimilated in ocean models to test them against real data, improve accuracy of models, or to force models. The early source of information about surface currents were pre-paid stamped drifting cards released at sea and mailed back to scientists upon retrieval in some parts of the ocean. After the 1970s, it became possible to track drifting buoys, or "drifters," via satellite tracking, and thus, the surface currents of all oceans have been measured. A wide program of drifters release has been running in the

Arctic for some time, and position and velocity data have been analyzed from ocean drifters in many areas (Mensa et al., 2018; Proshutinsky et al., 2019).

At present, drifter data are commonly available online and are a part of the general databases of ocean data about the Arctic (Bayankina et al., 2017; Zweng et al., 2018). A repository collecting ocean data is available from the Arctic Data Committee (https://arcticdc.org/), and the International Arctic Buoy Programme (IABP) also contains data from a network of buoys, with an average of 25 buoys in service at any time. In addition, the IABP maintains a network of drifting buoys to provide meteorological and oceanographic data for real-time operational requirements and research purposes including support to the World Climate Research Programme (WCRP) and the World Weather Watch (WWW) Programme. These data are permanently archived with the NSF Arctic Data Center and are also available through the IABP website. NOAA@NSIDC maintains these pages in cooperation with IABP to promote the use of these data and provide descriptive information that may be difficult to find elsewhere.

Satellite

Satellites provide real time, global, high space, and time resolution observations of key oceanographic variables that are essential to constrain ocean models through data assimilation (Le Traon et al., 2015). Oceanographic relevant data, e.g., altimetry and sea surface temperature (SST), can be assimilated in models, but a peculiar feature in the Arctic is sea ice, whose presence is relevant for debris transport and accumulation. Satellite derived data can provide key information about ice cover, formation, and properties. A set of repositories are available from NASA (www.nasa.gov) or from the Copernicus program (https://www.copernicus.eu/en).

Time series

Many oceanographic arrays have been deployed in the Arctic, especially after the most recent International Polar Year (2007-2009). Starting from the seminal work by Aagard and Greisman, 1975, many papers described the exchange of mass between the northern part of the oceans and the Arctic. Many studies are related to climate change but information about water masses exchange is relevant for marine litter studies as well. A summary of the current state of information on fluxes between oceans and Arctic can be found through the ASOF international working group (https://asof.awi.de/).

Data ecosystem map

In the future, finding tools and structures to combine and interlay data has the potential to improve modeling efforts and outputs. The Arctic Data Committee (ADC) has produced a map of the Arctic data management “ecosystem” or “universe,” a combined effort of the International Arctic Science Committee (IASC) and the Sustaining Arctic Observing Networks program (SAON). It is a concept map, indicating projects, services, and relationships, as well as a geographic map indicating locations.

The map effort was started during the first meeting of the ADC in Potsdam, Germany, November 2014 and is an ongoing activity. A prototype database and visualization tool has been developed and is scheduled for release soon (https://arcticdc.org/products/data-ecosystem-map). Many data useful for modeling litter in the Arctic can be downloaded from this site.

In addition to these existing data sources, modeling subject matter experts identified further data that would be necessary or helpful to improve the modeling of marine-litter movement within and into the Arctic, including:

- **Ocean currents** – additional and higher resolution data on ocean currents within and into the Arctic, particularly at the inflow and outflow gateways, as well as data on behavior in relation to freshwater inflow.
- **Sea-ice characteristics** – general behavior, formation and melt, changes from multi-year to seasonal ice, etc. with special focus on their interactions with marine litter and marine plastics.
- **Ocean surface winds and waves** – additional and higher resolution data on ocean surface conditions, as well as potential changes in the climate system that may affect the frequency, severity, and behavior of storms.

Additional data on the general behavior of marine litter also would be important, including plastic degradation and density changes over time due to biofouling, especially in Arctic conditions.

Additionally, specific information on the interaction between marine litter and sea ice, including how and under what conditions litter is entrained and thus transported within sea ice. Some limited work on general behaviors has been done, but primarily outside of the Arctic, and no specific studies on plastic behavior in sea ice were identified. Specific litter fragmentation rates as a function of ice formation rates would also be essential.

4.4.5 Long-term benefits

Although existing modeling capabilities in the Arctic are limited, in the long term, a more developed modeling approach could provide valuable insights into debris pathways within and into the Arctic, behavior of debris within the Arctic, and the relative influx and impact of local vs. long-range sources.

A more developed modeling approach could also help to identify and prioritize particular monitoring sites or an overall monitoring site-selection strategy by giving a clearer picture of likely areas of deposition for different types of marine litter. These monitoring sites, in combination with modeling data, could help elucidate the relative contribution and role of local debris introduction versus long-range debris sources because these differentiations are often challenging based on the commonality of many items and the degradation of material over time. Those long-range sources could also include atmospheric inputs of MP (Bergmann et al., 2019), which could be better understood in terms of their relative contribution to marine litter and MP loads in the Arctic through modeling.

As previously identified, there is relatively little data or understanding of the relative influence or contribution of riverine litter input to the Arctic, though it is known to be a significant driver in other areas. Improved modeling would help address this gap and inform prioritization of monitoring sites, and also mitigation actions.

Prognostic modeling at multiple timescales could also be very valuable in particular with the increasing use of Arctic resources for hydrocarbons, fishing, tourism, and other uses, by showing the potential litter distribution patterns under different future scenarios both in terms of litter inputs as well as forcing dynamics.

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4.5 Synergies with other research and monitoring programs

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A wide range of monitoring and research programs are taking place throughout the Arctic. Most Arctic countries have established national contaminant monitoring programs 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). Additional monitoring efforts taking place in the Arctic, but not specific to the Arctic, address seafood safety with a focus on maximum limits set by the EU and report the levels of legacy contaminants to food safety authorities (Jushamn et al., 2011, 2013a, b; Maage et al. 2017). As well, several Arctic species are monitored for population (e.g., Irons et al., 2015), and water is monitored for pH, temperature, salinity, CO_2, nitrogen, algae growth, and radioactivity (Skjerdal et al., 2017). Sound contamination is also monitored in some regions (Tyack et al., 2021). To minimize extra costs for litter and microplastics (MP) monitoring, synergies with existing programs and infrastructure may be sought.

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 (i.e., 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 or populations) are based on considerations of the statistical power needed in terms of sample sizes 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.

Limitations in using existing frameworks for implementing new monitoring objectives may result from the fact that litter and MP pollution can differ from the pollution with chemical contaminants in terms of sources, transport pathways, degradation, and/or environmental accumulation (Rochman, 2015). Thus, specifically optimized strategies and designs may be needed for litter and MP sampling and monitoring to account for these differences in environmental fate.

Additionally, litter and MP monitoring should ideally have a complementary citizen-science component because there are several ways in which citizen scientists can contribute to monitoring litter, and to date, these citizen scientists have not played a large role in existing monitoring programs in most regions in the Arctic.

4.5.1 Including litter and microplastics monitoring in ongoing contaminant monitoring programs

Some of the existing contaminant monitoring programs in the Arctic are briefly presented in the sections covering abiotic and biotic matrices. They include a suite of initiatives that collect samples, determine contaminants in the environment, and contribute to the circumpolar AMAP assessments, such as those on persistent organic pollutants (Dietz et al., 2013; Rigét et al., 2019). In several existing programs on biotic and abiotic compartments, there is potential for including litter and MP monitoring, as the following example illustrates: in the Canadian Arctic, seabirds have been collected under the Northern Contaminants Program for contaminants monitoring since the 1970s. Seabird eggs and individuals are collected with local Inuit community members and are then used to track trends in concentrations of legacy and emerging contaminants over time (Letcher et al., 2010; Braune and Letcher, 2013; Braune et al., 2014a, b). Since 2008, seabirds collected under this program have also been used to monitor plastic pollution (Poon et al., 2017; Provencher et al., 2018; Lu et al., 2019). For seabirds, sampling for litter and MP was particularly easy to add to the existing program because carcasses were already being collected to study the livers, the typical tissues examined for contaminants. During the dissections in communities, it was 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 (Provencher et al., 2019) and thus provides standardized metrics for global comparisons (Provencher et al., 2017).

4.5.2 Including litter and microplastics monitoring in other types of programs

In addition to the contaminant-focused monitoring programs, there are a variety of other opportunities for collecting samples that can provide information on litter and MP in the region. For example, fishery management-based programs are being used in Canada and Norway to collect fish samples for litter and MP assessments. In the Canadian Arctic, fisheries monitoring programs have collected samples of Arctic char (*Salvelinus alpinus*) for litter and MP assessments (B. Hamilton, *personal communication*).

Additionally, some research programs can collect non-target species, e.g., bycatch in fisheries, for litter and MP monitoring. This has been applied in Arctic Canada where seabirds accidentally caught by fisheries (Northern Fulmars, *Fulmarus glacialis*; Anderson et al., 2018) have been examined for plastics (Mallory et al., 2006). In Norway, ecosystem cruises, which contribute to the population monitoring of seafood fish species for sustainable catch, now house manta trawling equipment for plastic in water and plankton, and they also record macroplastic observations (Grøsvik et al., 2018)

Ships of opportunity can also be used to survey litter on the surface of the water via cruises. Mallory et al., 2021 reported floating litter throughout the Canadian Arctic as part of at-sea bird surveys aboard ice-breaking vessels. Based on at-sea surveys covering 263,543 km of marine survey transects, anthropogenic debris was observed floating in marine 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). Such data collection may help fill in knowledge gaps in regions where only a few vessels transit each year.

Community-based monitoring can contribute to monitoring litter and MP in the Arctic region. For example, Norwegian northern minke whale (*Balaenoptera acutorostrata*) hunters report their plastic litter observations to researchers. In Canada, Indigenous hunters are collaborating with research teams to contribute samples from subsistence harvests for litter and MP work, including ringed seals (*Pusa hispida*; Bourdages et al., 2020), beluga, (*Delphinapterus leucas*; Moore et al., 2020), and walrus (*Odobenus rosmarus*; underway in Nunavut; J. Provencher, *personal communication*). Indigenous knowledge platforms like the SIKU program in northern Canada (https://sikuatlas.ca/index.html) and other community-based programs could be expanded to include litter observations.

There may also be opportunities for industry and tourism operators to contribute to litter and MP monitoring. For example, Mallory et al., 2021 used a rapid shoreline survey technique aboard a tourism cruise ship to survey shoreline litter. This study sought to implement a variety of methods used to study plastic debris in the marine environment of Arctic Canada and west Greenland, where there are limited data currently. In this study, coastal debris was dominated by plastic pieces (73%), but also metal (8%), glass (8%), processed wood (7%), cardboard (2%), and cloth (< 1%), thereby helping to understand what litter is found in the region (Mallory et al., 2021). These numbers reflect other Arctic observations in which plastic dominated marine litter observations in the upper 60 m depth (86.4 ± 16.5% by weight) over a seven-year study period (Grøsvik et al., 2018). These types of rapid assessments should be considered to gain knowledge about litter and MP in regions where data are minimal.

4.5.3 Ongoing monitoring programs

Given that litter and MP are ubiquitous and have been found in nearly all environmental compartments in the Arctic (e.g., snow, ice, water, sediments, beaches, the sea floor, zooplankton, fish, birds, and mammals), it would be advisable to engage with ongoing monitoring programs to ensure efficient use of samples and resources. Additionally, benefits accrue in learning from past experiences and exploring multi-purpose uses of supporting data.

Future sampling can be carried out in collaboration with existing programs that are already in place (Figure 4.8) and sampling (i.e., collection method or species) can be implemented across most of the Arctic without additional need for infrastructure or technology development.

Possibilities for synergies will be further explored in the AMAP *Litter and Microplastics Monitoring Plan*, which will accompany the monitoring guidelines.

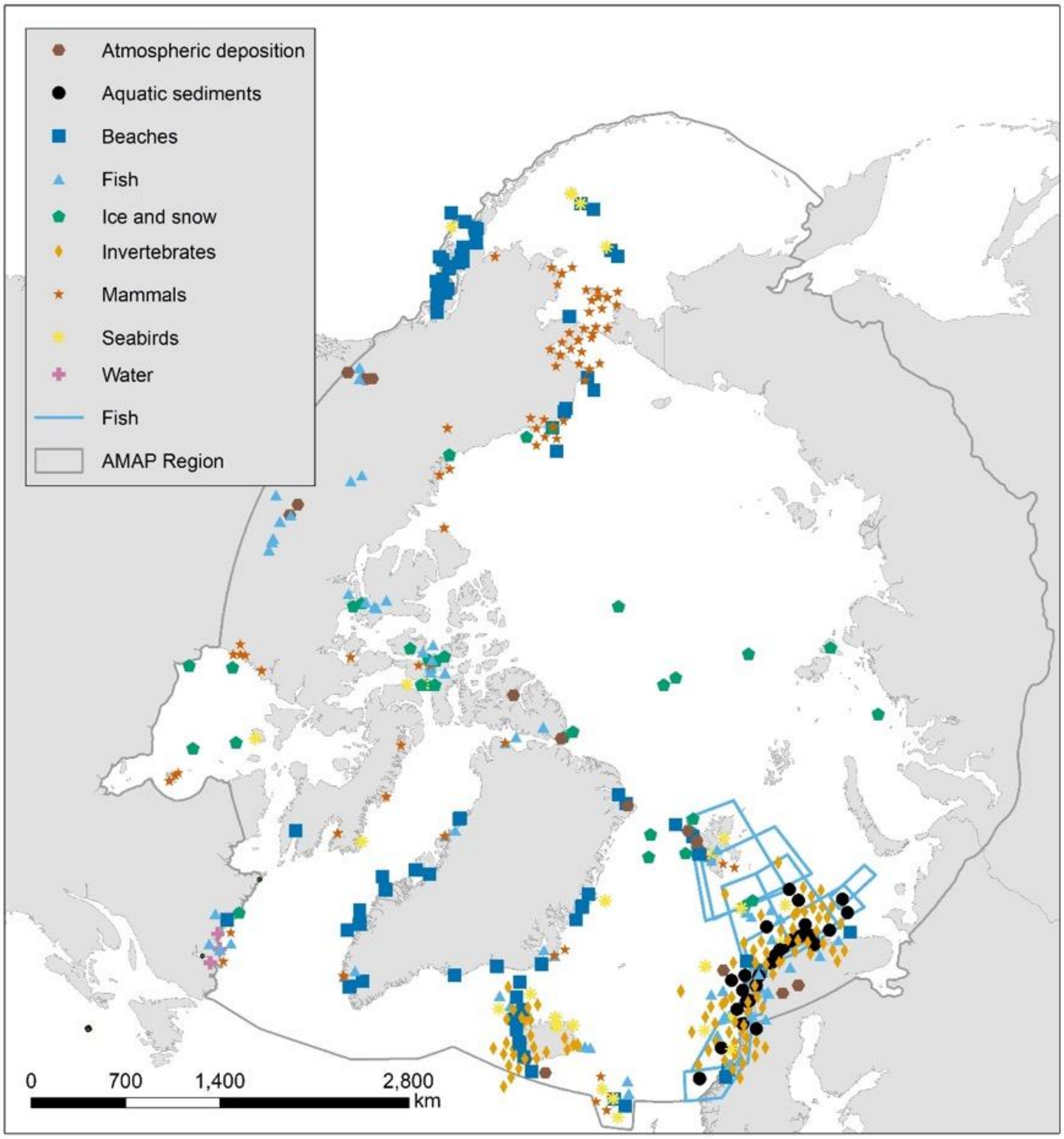

Figure 4.8 Locations of current chemical contaminants (atmosphere deposition, ice and snow, invertebrates, fish, sediments, and water), litter (via beaches), and population (seabirds, fish, and mammals) monitoring programs in the environmental compartments examined in the *AMAP Litter and Microplastics Monitoring Guidelines* in which current monitoring could be augmented to include additional metrics to collect information on litter and MP alongside existing contaminant monitoring programs. Points are jittered to prevent overlap and make the symbols visible to demonstrate the spread of the data.

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5.0 Future Work for AMAP

The current Monitoring Plan is envisaged as part of a phased approach to work on litter and microplastics (MP). The Monitoring Plan has been based on the best available knowledge at the time of writing, and it is recognized that future work should focus on other aspects of litter and MP in the environment (i.e., contaminants and biological effects), and should revisit technical guidance and monitoring plan recommendations on a regular cycle to maintain up-to-date, evidence-based decision making. Reviewing and updating are important because this topic is under considerable development, therefore the documents must be reviewed at regular intervals.

2019-2021 – Technical guidance and monitoring plan development for litter and microplastics

This first phase focuses solely on the monitoring of litter and MP in the Arctic, to create a framework that countries can use to implement harmonized litter and MP monitoring to ensure that spatial and temporal trends may be assessed in the future. The Monitoring Plan is part of this first phase, which also includes detailed monitoring guidelines.

Future work – Gap analysis and review of the effects from litter and microplastics with a focus on chemical contaminants from plastic pollution

Following the monitoring framework in phase 1 (2019-2021), a review and gap analysis have been proposed on the state of knowledge of known effects of litter and MP, including entanglement of biota and ingestion of plastic. This phase will also address plastic as a vector for chemical contaminants and its biological effects. Although the first phase will have focused strictly on monitoring the physical presence of plastic pollution, this next phase of the work will focus on the chemical contaminants of litter and MP and their effects. Litter and MP are both particulate and chemical contaminants, thus this effects project will include both the chemical contaminant effects and the potential negative effects on ecosystems due to the particulate nature of plastics (i.e., vectors for introduced species, inflammations, clogging of digestive tracts, effects on metabolism).

Future work – Updating the AMAP Litter and Microplastics Monitoring Guidelines and the Monitoring Plan

It is recognized that there is a great deal of work underway to develop methods in relation to assessing plastic pollution in the environment, specifically for MP and nanoplastics. For example, although MP and nanoplastics in consumed wild species' tissues is of great interest, there are currently no standardized methods available that detect nanoplastics in wild tissue samples. Research and method development are underway, and new advances are expected in the next two to five years given the large range of projects being carried out. Therefore, it is recommended that the AMAP Litter and Microplastics Monitoring Guidelines and Monitoring Plan be revisited and revised on a two-five year cycle to update recommendations and align them with emerging research findings.

Future work – Trend monitoring assessment

The third phase of AMAP's work in this field will be to examine and synthesize all available material on the spatial and temporal scales similar to other long-term trend assessments under AMAP. Ideally, this work will be done once monitoring programs have been put in place for several years using the framework developed in phase 1. This third phase will hopefully conduct an initial trends assessment and also identify gaps in monitoring programs that should be prioritized to achieve a better understanding of trends. This third phase may also include some power analyses of current data to address questions around the frequency of sampling for any datasets available at the time.

Future work – Effect monitoring assessment

The fourth phase of the project will be a trend assessment of the known effects from litter and plastic pollution and any trend monitoring in plastic-derived contaminants. Any new effects information will be incorporated.

Trawlnet on shoreline.

Acronyms and Abbreviations

ABS	Acrylonitrile butadiene styrene
ACTRIS	Aerosols, Clouds, and Trace gases Research InfraStructure Network
ADC	Arctic Data Committee
AMAP	Arctic Monitoring and Assessment Programme
AML	anthropogenic marine litter ASOF: Arctic Subarctic Ocean Fluxes
ASOF	Arctic-Subarctic Ocean Fluxes
ATR-FTIR	attenuated total reflection Fourier transform infrared
AUV	Autonomous underwater vehicle
AWI	Alfred Wegener Institute
BWP	brake wear particles
CAFF	Conservation of Arctic Flora and Fauna
CBird	Circumpolar Seabird Expert Group
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CTD	Conductivity, Temperature, and Depth
CP	Curie point
DFO	Department of Fisheries and Oceans (Canada)
DIW	deionized water
DOME	ICES Environmental Database
DSC	differential scanning calorimetry
EBAS	atmospheric database
ECCC	Environment Canada and Climate Change
EcoQO	ecological quality objective
EGA	evolved gas analysis
EGU	European Geosciences Union
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
EPDM	ethylene propylene diene monomer
EPS	expanded polystyrene
EU	European Union
EU TG-ML	MSFD Technical Group on Marine Litter
FFL	Fishing for Litter
FO%	frequency of occurrence in percent
FPA	focal plane array
FRAM	FRontiers in Arctic marine Monitoring
FTIR	Fourier-transform infrared
GAW	Global Atmosphere Watch Programme
GC	gas chromatographic
GES	good environmental status
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GIT	gastrointestinal tract
GLP	general laboratory practices

H_2O_2	hydrogen peroxide
HAUSGARTEN	Long-Term Ecological Research Station observatory in the Fram Strait
HDPE	high-density polyethylene
HELCOM	Helsinki Commission
HPLC	high-performance liquid chromatography
HVAC	heating, ventilation, and air conditioning
IABP	International Arctic Buoy Programme
IASC	International Arctic Science Committee
IBTS	International Bottom Trawl Surveys
ICES	International Council for the Exploration of the Sea
ISO	Organization for Standardization
ISTDpy	internal pyrolysis process standards
IWC	International Whaling Commission
KOH	potassium hydroxide
LDPE	low-density polyethylene
LMEG	Litter and Microplastics Expert Group
LOD	limit of quantification
LOQ	lowest concentration
LTER	long term ecological research
MALINOR	Mapping marine litter in the Norwegian and Russian Arctic seas
MARPOL	International Convention for the Prevention of Pollution from Ships
MCT	mercury cadmium telluride
µFTIR	micro-Fourier transform infrared
ML-RAP	Marine Litter Regional Action Plan
MP	microplastics
Milli-Q/MQ water	water that has been purified using resin filters and deionized to a high degree by a water purification system manufactured by Millipore Corporation
MIZ	marginal ice zone
MSFD	Marine Strategy Framework Directive
NaI	sodium iodide
NaOCl	sodium hypochlorite
NASA	National Aeronautics and Space Administration
NCP	Northern Contaminants Program (Canada)
NEMO	Nucleus for European Modelling of the Ocean
NFR	Norwegian Research Council
NGO	Non-governmental organization
NILU	Norwegian Institute for Air Research
NML	natural marine litter
NOAA	National Oceanic and Atmospheric Administration (United States)
NR	Nile Red
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
OECD	Organisation for Economic Co-operation and Development
OFOS	Ocean Floor Observation System

OGCM	ocean general circulation models
OM	organic material
OSF	Open Science Framework project
OSPAR	Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)
PA	polyamide
PAME	Protection of the Arctic Marine Environment
PBDE	polybrominated diphenyl ethers
PC	polycarbonate
PE	polyethylene
PEEK	polyether ether ketone
PET	polyethylene terephthalate
PEVA	polyethylene-vinyl acetate
PP	polypropylene
PTFE	polytetrafluoroethylene
PU/PUR	polyurethane
PVC	polyvinyl chloride
pyr-GC/MS	pyrolysis gas chromatography mass spectrometry
QA/QC	quality assurance/quality control
QUASIMEME	Quality Assurance of Information for Marine Environmental Monitoring in Europe
ROV	remotely operated underwater vehicle
SAMP	suspended atmospheric MP
SAON	Sustaining Arctic Observing Networks program
SD	standard deviation
SDS	sodium dodecyl sulphate
SEA-MDI	Southeast Atlantic Marine Debris Initiative
SEM	scanning electron microscopy
SLS	sodium lauryl sulphate
TED	thermo extraction desorption
TED-GC/MS	thermo extraction desorption chromatography mass spectrometry
TGA	thermogravimetric analyzers
TMAH	tetramethylammonium hydroxide
TOPIOS	Tracking of Plastics in Our Seas
TWP	tire wear particles
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WWW	World Weather Watch Programme
ZWIA	Zero Waste Standards and Policies

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