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The power of multi-matrix monitoring in the Pan-Arctic region: plastics in water and sediment

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Abstract

Litter and microplastic assessments are being carried out worldwide. Arctic ecosystems are no exception and plastic pollution is high on the Arctic Council's agenda. Water and sediment have been identified as two of the priority compartments for monitoring plastics under the Arctic Monitoring and Assessment Programme (AMAP). Recommendations for monitoring both compartments are presented in this publication. Alone, such samples can provide information on presence, fate, and potential impacts to ecosystems. Together, the quantification of microplastics in sediment and water from the same region produce a three-dimensional picture of plastics, not only a snapshot of floating or buoyant plastics in the surface water or water column but also a picture of the plastics reaching the shoreline or benthic sediments, in lakes, rivers, and the ocean. Assessment methodologies must be adapted to the ecosystems of interest to generate reliable data. In its current form, published data on plastic pollution in the Arctic is sporadic and collected using a wide spectrum of methods which limits the extent to which data can be compared. A harmonised and coordinated effort is needed to gather data on plastic pollution for the Pan-Arctic. Such information will aid in identifying priority regions and focusing mitigation efforts.

Key words: environmental sampling, microplastic(s), assessment, ecosystem, pollution, marine, freshwater, terrestrial, Anthropocene, Arctic

Résumé

Des évaluations des déchets et des microplastiques sont effectuées dans le monde entier. Les écosystèmes arctiques ne font pas exception et la pollution plastique figure en bonne place dans le programme du Conseil de l'Arctique. L'eau et les sédiments ont été identifiés comme deux des compartiments prioritaires pour la surveillance des plastiques dans le cadre du Programme de surveillance et d'évaluation de l'Arctique (AMAP, *Arctic Monitoring and Assessment Programme*). Des recommandations pour la surveillance de ces deux compartiments sont présentées dans cette publication. Pris séparément, ces échantillons peuvent fournir des informations sur la présence, le devenir et les impacts potentiels sur les écosystèmes. Ensemble, la quantification des microplastiques dans les sédiments et l'eau d'une même région produit une image tridimensionnelle des plastiques, non seulement un instantané des plastiques flottants à la surface ou dans la colonne d'eau, mais aussi une image des plastiques atteignant le littoral ou les sédiments benthiques, dans les lacs, les rivières et l'océan. Les méthodologies d'évaluation doivent être adaptées aux écosystèmes d'intérêt pour générer des données fiables. Dans leur forme actuelle, les données publiées sur la pollution plastique dans l'Arctique sont sporadiques et recueillies à l'aide d'un large éventail de méthodes, ce qui limite la possibilité de comparer les données. Un effort harmonisé et coordonné est nécessaire pour recueillir des données sur la pollution plastique dans la région panarctique. Ces informations permettront d'identifier les régions prioritaires et de concentrer les efforts d'atténuation. [Traduit par la Rédaction]

Mots-clés : échantillonnage environnemental, microplastiques, évaluation, écosystème, pollution, marin, eau douce, terrestre, Anthropocène, Arctique

1. Introduction/context

The Arctic, a vulnerable region susceptible to changing environmental conditions, has not escaped the influence of anthropogenic activities. One concern is the presence of litter and microplastics (plastics < 5 mm in size). Records from Alaska dating back to the 1960s include the occurrence of plastic debris and the relative consequences for marine life (Threlfall 1968). The supply of litter and microplastics to and within the Arctic includes long-range transport, having been carried by sea currents (Lusher et al. 2015; Bergmann et al. 2016; Cózar et al. 2017; Kanhai et al. 2018; Tekman et al. 2020; Pogojeva et al. 2021), sea ice—formation, movement, and melting—(Obbard et al. 2014; Peeken et al. 2018; Kanhai et al. 2020; von Friesen et al. 2020; Kim et al. 2021), riverine input (Frank et al. 2021; Yakushev et al. 2021), input by the atmosphere (Bergmann et al. 2019; Evangeliou et al. 2020), as well as localised input from urban centres (Rist et al. 2020), littering, fishing, dumping of sewage or garbage, and wastewater treatment facilities (Granberg et al. 2019; von Friesen et al. 2020; Mallory et al. 2021). Unfortunately, there is a paucity in the available published literature on the origin of detected plastic litter, which hinders an understanding of the relative importance of sources. Considering that wastewater treatment and waste management infrastructure are absent or insufficient in the Arctic (Gunnarsdôttir et al. 2013), local sources or pathways may be underestimated. An accurate assessment of source contribution is required for the successful implementation of pollution avoidance and mitigation measures (i.e., improved wastewater treatment and waste management).

Critical to the discussion of microplastics in the Arctic is the movement of water masses through the region, as well as the distributions of different kinds of sedimentary environments. Litter and microplastics can be transported within water bodies from point sources such as wastewater outlets to nearshore and offshore areas, and settle in shoreline sediment, beach sand, shoreline gravel, and benthic zones including the deep-ocean floor (Lots et al. 2017; Bosker et al. 2018; Piñon-Colin et al. 2018; Abel et al. 2021). The Arctic Monitoring and Assessment Programme (AMAP) region covers 18 large marine ecosystems, influenced by several marine current systems and hundreds of freshwater rivers (Fig. 1) (Protection of the Arctic Marine Environment Working Group (PAME) 2013*a*, 2013*b*). The North Atlantic Current brings relatively warm water to the Arctic between Iceland and Europe, while the Bering Strait brings a much smaller, cooler water body mass into the Arctic from the North Pacific region (Timmermans and Marshall 2020). The Central Arctic Ocean is a relatively deep-water body (~4000 m mean depth) consisting of two basins (Canada and Eurasian basins), with passageways to the Arctic Ocean from the Pacific and the Atlantic being fairly shallow (<1000 m; Timmermans and Marshall 2020). The Central Arctic Ocean remains ice covered throughout most of the year, preventing surface currents from penetrating this region, although the sea ice cover is in retreat in all seasons. Climate models project a continued loss of Arctic sea ice in the coming decades as a result of climate change. Summer sea ice is expected to disappear sometime before the middle of this century (Dörr et al. 2021). While the marine Arctic is limited to the traditional AMAP region, the watersheds that feed into the Arctic expand well past Arctic regions, into temperate climate zones in both Eurasia and North America. The discharge of several massive rivers makes terrestrial and coastal influences particularly strong in the Arctic Ocean. The Arctic constitutes approximately 1% of the global ocean volume, yet the Arctic Ocean receives upwards of 10% of the global river discharge. Consequently, the freshwater component of the Arctic is of incredible importance (Holmes et al. 2011).

As water bodies contribute to the movement and dispersal of plastics within freshwater, coastal, and pelagic realms they act as conduits to sedimentary environments. Here, the link between water and sediment may not be straightforward and it is, for example, thus not obvious to sample sediment and water when aiming to link the presence of plastic litter to the discharge from a source. However, discrete aquatic particle flux events sink to accumulate long-term running averages of particle supply in the sedimentary record. The fate of microplastics differs, when it comes to processes of transportation and deposition (i.e., certain microplastics may remain in suspension and are further transported, while others settle rapidly), such that the complete microplastic pollution profile of an area may not be obtained without considering both environments (Rochman et al. 2019; Clayer et al. 2021). Sedimentation in marine systems has long been understood as a process of benthic-pelagic coupling with horizontal transport processes dominating the vertical deposition of particulate matter (Graf 1992). Thus, the design of any monitoring programme needs to take these aspects into consideration. Sediments, both freshwater and marine, have been identified as sinks for litter and microplastics whether due to the rapid sinking of high-density plastic particles (Woodall et al. 2014; Kowalski et al. 2016; Erni-Cassola et al. 2019; Gomiero et al. 2019; Haave et al. 2019; Tekman et al. 2020), settling caused by biofouling (Kaiser et al. 2017; Rummel et al. 2017), or incorporation into sinking organic hetero-aggregates, e.g.,

Fig. 1. The Arctic Monitoring and Assessment Programme (AMAP) region and the 18 large marine ecosystems (LMEs) it includes. AMAP comprises eight member states: Canada, Denmark, Greenland, Faroe Islands, Finland, Iceland, Norway, Russian Federation, Sweden, and United States; and six permanent participants: Arctic Athabaskan Council, Aleut International Association, Gwich'in Council International, Inuit Circumpolar Council, Russian Arctic Indigenous Peoples of the North, and Saami Council. Map constructed in ArcGIS Pro with Shapefiles from AMAP (Steenhuisen and Wilson 2013) and PAME (Protection of the Arctic Marine Environment Working Group (PAME) 2013*a*, 2013*b*). Map Projection: WGS 1984 Web Mercator (auxiliary sphere). Coordinate system: WGS 1984.

marine snow (e.g., Long et al. 2017; Porter et al. 2018) or ice algae. Given the susceptibility for sediment in calm areas to accumulate and sequester microplastics, and the potentially weak upward transport of already buried plastics (≥100 μm) (Brandon et al. 2019; Fan et al. 2019; Näkki et al. 2019; Courtene-Jones et al. 2020), these depositional systems represent a temporal record of plastic input to aquatic environments (e.g., Dahl et al. 2021). However, microplastics settled on the seafloor or stranded on shorelines may still be subsequently resuspended and further transported with water currents or redistributed within the sediment column (Enders et al. 2019; Kane et al. 2020; Martin et al. 2022).

Microplastics have now received substantial targeted attention globally due to their ubiquitous yet challenging to quantify environmental presence (Zhang et al. 2020). The array of literature on microplastics in the Arctic has recently been reviewed (Halsband and Herzke 2019; Tirelli et al. 2020; Singh et al. 2021); therefore, information pertaining to the state of the science in Arctic waters and sediment is presented in the Supplementary Information. Generally, microplastics are more abundant (by individual item count) than larger plastics and other litter items. However, they also require tailored methods for reliable detection and environmental enumeration. Microplastic enumeration (by size, shape, and polymer composition) is significantly impacted by methodological choices, hindering comparison between reported microplastic concentrations (and morphologies) across individual studies. Thus, results from different studies need to be considered carefully and put in context.

With the growing requirements by countries to quantify current or baseline levels of litter and microplastics in their environments, it is necessary to choose the most appropriate tool, or combination of tools to perform this task. Many of the standards and methods for microplastics research developed south of the Arctic, and are ill-suited to Arctic environments. For example, a systematic study of 361 published, English-language shoreline surveys encompassing 3284 sample sites globally, found only 4% of sites included coarse sediment and only 2.5% of sites are sampled in the presence of ice or snow (Melvin et al. 2021). Studies sometimes report choosing sandy locations for sampling in landscapes dominated by ice, snow, or rocky shorelines to comply with standardised shoreline protocols for sand, introducing a landscape bias in results, which may hardly be representative of Arctic environments (Melvin et al. 2021). As microplastics are identified in many different sample types, the design and development of an Arctic monitoring programme will benefit from studies which address more than one environmental matrix. Such an approach is now being considered under the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP 2021). Sediment and water sampling provide an ideal example of multi-matrix monitoring, but there are several aspects to consider when planning such a programme. These include local site conditions such as identifying accumulation and erosive bottoms, sedimentation rates, presence of fauna, and proximity to areas of anthropogenic activity. The inclusion of microplastics in water and aquatic sediment monitoring programmes must consider the complexities surrounding microplastic distribution, and focus on useful and affordable actions to collect time series; which are the primary tool to verify whether mitigation measures are effective (Maximenko et al. 2019; Bank et al. 2021).

The Arctic region is composed of complex and unique ecosystems, including freshwater, marine, and terrestrial components spread over eight Arctic states and the traditional territories of six permanent participant Indigenous groups. Monitoring this region requires collective assessment. Cooperation at the Pan-Arctic level is the primary goal of the Arctic Council. Access to facilities, the availability of researchers and volunteers, and the selection of assessment methods will vary between monitoring programmes. Therefore, a combination of approaches and methodological sensitivities may be necessary to build a picture of the scale of litter and microplastic pollution. Here, we present the complementary application of water and sediment sampling focused on microplastics in the Arctic region by (1) discussing the methods currently used, and those recommended for integration into monitoring programmes, (2) exploring the benefits and added value of future water and sediment monitoring efforts, and (3) highlight potential opportunities for Arctic monitoring programme development.

2. Requirements for developing monitoring programmes of microplastics in the Arctic

Selecting sampling locations in the Arctic can be constrained by available facilities and infrastructure. However, all monitoring programmes must align their methods with specific programme goals and account for environmental conditions. Investigations of accumulation areas, source contribution (e.g., effluents from wastewater treatment plants or industries), transfer routes (e.g., rivers), or long-range pathways (e.g., atmospheric fallout) may all require tailored approaches, particularly where there are pressing concerns for the scientific community or Arctic Peoples. The methods chosen must align with the purpose of the monitoring programme but should also acknowledge the need for harmonised methods and (or) recommended guidelines. It should not be a static process, rather the methods should be flexible enough for further improvement and technological development (Lusher et al. 2021). For example, methods that allow for the quantification of the smallest microplastics are vital to understand the impacts on organisms, such as zooplankton, which are important entry routes of microplastics into aquatic food webs (Rist et al. 2020). However, these methods still require further method development and testing. The smallest microplastics (ca. 1–300 μm) and especially nanoplastics (<1 μm) require tailored (and increasingly rigorous) approaches from sampling strategy to laboratory analysis (Brander et al. 2020). Defining what constitutes environmentally representative samples and appropriate quality control/quality assurance for nanoplastics remains an ongoing research topic in its early stages, largely because of technical limitations (Wang et al. 2021). However, nanoplastics have already been identified and reported in both Polar regions (Materić et al. 2022) and an understanding of these particles will be required to gain insight into the complete environmental life cycle of plastics in the Arctic. Current practices for the quantification of the smallest microplastics and nanoplastics can be cost prohibitive, especially for community-based research institutions in the Arctic. Therefore, defining pressing knowledge needs and ascertaining the technical readiness of responsible institutions must be considered before establishing any monitoring mandates addressing the smallest of plastic particles. Research design and methods should also be aligned with the priorities of Indigenous and Arctic communities who are not only potential end users of such data, but also often produce their own data or work in partnership with southern scientists and ought to be able to influence scientific design (Inuit Tapiriit Kanatami 2018; Liboiron et al. 2021). Sampling strategy will also vary depending on the targeted environmental compartment and the size of the plastics of interest. For example, manta or other neuston trawl sampling is impractical where there is high biomass, adverse weather conditions, or sea ice, and often only captures plastics >300 μm. Similarly, the choice of location for sampling aquatic sediment should consider sediment composition, and site-specific hydrodynamics, depending on the aim of the specific programme. International working groups have critically assessed methods and highlighted global monitoring considerations (e.g., GESAMP 2019), but did not consider the unique conditions of the Arctic. Here, we therefore focus on specific Arctic concerns within the context of global recommendations.

2.1. Collection of microplastic data

The most informative and sustainable way to design a monitoring programme with statistical power is to gain insight into the variation between samples collected in the area of interest. A power study is useful in this regard. The approach taken should be similar for both sediment and water. Patchiness will determine the number of replicates necessary to obtain sufficient statistical power and representativeness for a given region (Fisner et al. 2017; GESAMP 2019; Korez et al. 2019). It will thus be necessary for any monitoring programme to initiate a power analysis per location to assess the variability of plastic concentrations (Sokal and Rohlf 1995). At present, not enough published data are available from any given region to determine the number of stations, volumes, and replicates required for Arctic water and sediment samples. 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. When added to patchiness, temporal variations in microplastic occurrence and changing environmental conditions—especially on shorelines—become complicating factors in designing a monitoring programme, particularly with high seasonal variability (Fisner et al. 2017). Recommended sampling frequency follows the aim of a monitoring programme and the type of environment under investigation, where requirements differ when assessing aquatic particle fluxes over short periods (days and months) or long-term sedimentary trends (years) (Graf 1992).

2.2. Collection of ancillary data

The collection of ancillary data is important to help monitor and understand the distribution and concentration of microplastics in the Arctic and the underlying environmental factors influencing this distribution. Ancillary data are generally easy to collect and can include such information as wind conditions, temperature, salinity, and chlorophyll *a* where applicable. The properties and origin of water masses may be identified using their temperature, salinity, or nutrient signature (e.g., Yakushev et al. 2021). This can be obtained from CTD (conductivity, temperature, and density) probes together with chlorophyll *a* measurements, which are widely used in monitoring programmes. Differentiating between water masses is important to identify drivers behind microplastic concentrations in the Arctic. A recent microplastics survey from Siberian rivers suggests that the low plastic concentration water from the river plumes spread on top of the Atlantic origin water with higher plastic content (Yakushev et al. 2021). An example of the application of ancillary data in microplastics research is the use of wind speed measurements, which is usually collected by all ships. Wind strongly mixes ice-free oceans, vertically displacing particles at the sea surface. Manta/neuston nets skim the surface and cannot sample subsurface microplastics. Subsequently, a correction factor is required. Kukulka et al. (2012) and Kooi et al. (2016) have proposed methods for estimating the vertical distribution of microplastics in a water column by using wind speeds and wave heights during sampling to model distribution. With an appropriate estimate of the vertical distribution of microplastics in the water column, it is possible to compare the density of microplastic from nets at different immersion depths (Michida et al. 2019). Another possibility is two-dimensional backtracking of particles by high-resolution modelling, with models such as FESOM (Tekman et al. 2020).

2.3. Consideration of contamination

One necessary, and increasingly central aspect of any field sampling campaign is the quantification of procedural contamination. Researcher-derived contamination is a serious issue in studies of microplastics. It is essential that any potential sources of contamination (primarily easily mobilised and shed fibres) are kept to a minimum and quantified, and at the very least assessed (Belontz and Corcoran 2021). Potential sources of contamination must be recorded, and where possible collected to act as a reference. Potential sources of procedural plastic contaminants in the Arctic include staff clothing, ships, skidoos, helicopters, or other vehicles, as well as equipment, and any plastics or paints used in the vicinity (Leistenschneider et al. 2021). During sample collection, efforts to prevent contamination should be enforced and all steps taken should be clearly reported. For all microplastic field investigations, field blanks collected in parallel to samples are strongly advised where practically possible (Brander et al. 2020). For all investigations of microplastics, sampling devices must be thoroughly cleaned before sampling and between samples, i.e., flushing nets with high volumes of (preferably filtered) water. As an example, Michida et al. (2019) recommended thoroughly cleaning the sample net from the outside before the start of the sampling run to ensure no particles remain. The rinse water can be scrutinised for particles. Blank samples for correction of air deposition of microplastics may be obtained by keeping an empty, opened sampling container or dampened filter papers (Woodall et al. 2015) in the location where sampling (or the transferral of sampled material) is being performed. Controls representative of sampling equipment (opening dimensions) are needed. These controls should give an indication of the number of airborne particles. It is also important to recognise that some equipment cannot be cleaned of all particles, e.g., plankton nets cannot be cleaned of all fibres between sampling. Therefore, the inclusion of fibres should be carefully considered when designing and implementing a monitoring programme utilising nets.

The number and types of microplastics in the blank samples define the detection limit for each collected sample and microplastic 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. An important consideration of Arctic research is the heavy use of synthetic materials to protect scientific parties working in the Arctic environment versus the often relatively low concentrations of microplastics estimated to be accumulating in many Arctic settings. Large sample volumes may be required to distinguish microplastic pollution levels from background procedural contamination (limit of detection/limit of quantification). Accounting for this should form a part of the development of Arctic monitoring programme procedures.

3. Recommended water sampling methods for microplastics in the Arctic

Given the complexities of sampling in the Arctic, and many different water bodies available for sampling, it is necessary to consider several different approaches depending on the requirements of specific surveys and research priorities. There are many methods available to collect surface water samples, including nets and pumps, which will allow the targeted assessment of small plastics and microplastic. Several recommended protocols have recently emerged for sampling microplastics, many of the available methods, as well as their application across several matrices, are at different levels of technical readiness (Table 1). As such, methods already suitable for monitoring have been identified, as well as those that show promise but need further research and development to validate their use in monitoring programmes. The methods chosen will influence the sizes of particles captured (Lindeque et al. 2020; Rist et al. 2020; Uurasjärvi et al. 2020; Tokai et al. 2021). Therefore, the choice of approach taken should reflect the method limitations and specific aim of the monitoring programme. Different sampling methods may be integrated into a single monitoring programme to cover different size classes of microplastics where this information is relevant (Ryan et al. 2020; Yakushev et al. 2021). Regardless of the method chosen, all samples collected should be rinsed/volume reduced with filtered water (with the addition of stacked sieves, if relevant) into suitable containers (preferably a marked non-plastic container). Processing should follow recommended procedures (see Supplementary Information for further details).

3.1. Surface water sampling: Inland, coastal, offshore

Manta net sampling is already commonplace around the world and can provide a somewhat harmonised data for surface microplastic concentrations (excluding fibres smaller than ~300 μm). For this reason, it has been recommended that this method of assessment is continued in the Arctic region while other methods are further validated, especially in inland and coastal water bodies. The application of net sampling in offshore areas will be heavily influenced by deployment conditions in these regions. Net sampling will typically capture larger particles, >300 μm, but depends on the net used. In doing so, however, this will under-represent the smaller-sized fraction of particles, which are of particular interest in terms of impacts or uptake by marine biota. Net sampling should be used with caution if a programme is attempting to quantify fibres; since they can stick to the net and may cross-contaminate samples. Nevertheless, until further methods are explored, surface net sampling has the highest technological readiness level and is already operational (e.g., in the Barents Sea; Havforskningsinstituttet, B.E. Grøsvik, personal observation, 2022).

A manta/neuston net can be deployed from a research vessel or other appropriate sampling platform for a period of 10–30 min, with a speed of between 1 and 3 knots depending on the prevailing sea conditions. An accurate measurement of the filtered water (frequently in 100s of m^3) must be collected using a flow meter attached to the net (e.g., Lusher et al. 2015). When a tow is complete, the net must be washed and rinsed with (preferentially filtered) water from the outside, and the cod-end sampler should be removed and (ideally) rinsed under contamination-controlled conditions. Samples should be washed using filtered water and can be rinsed through a series of clean metal sieves (e.g., 5 mm and 200 μm) to fractionate samples before analysis. The target microplastics should reflect the mesh size of the apparatus. Manta/neuston nets have limited use in rough seas, as waves can affect their position in the water, causing differences between Global Positioning System (GPS) and flow meter data, and subsequently impact the calculated results (Lusher et al. 2015; Michida et al. 2019). The vertical position of plastics in the upper layers of the water column can be affected by wind speed (Kukulka et al. 2012), often with particle concentration being negatively correlated with wind speed and stress, such that higher densities are observed when samples are collected during relatively low wind speeds. A correction coefficient (2.06, max 8.97) has previously been applied to address the undercounting of microplastics (>700 μm) resulting from wind-induced mixing in the Mediterranean (Suaria et al. 2016) and also applied in the Arctic investigations (e.g., Tošić et al. 2020). Given that sea state can impact sampling efficiencies, it is only recommended to carry out net sampling under calm conditions in inshore areas.

Large sample volumes are often necessary to obtain sufficient sample sizes and concentrations of microplastics above limits of detection, especially in waters where concentrations might be low. Furthermore, large-volume pump samples can be obtained with ancillary/metadata collected simultaneously, which facilitate comparisons between sampling and environmental conditions and measured microplastic concentrations (e.g., Lusher et al. 2015; Tekman et al. 2020; Yakushev et al. 2021). Sampling microplastics in the water column can be approached using vessels of opportunity or through targeted efforts. Their application in offshore waters has been shown to be successful, although inshore locations will require further validation as local biological processes and the suspension of fine particulate matter may impede results or add additional processing steps.

Further method development should also be directed to the use of CTD rosettes in surface waters. Currently, validation studies are lacking comparisons. Providing all bottles are fired together, CTD rosettes can collect a reasonable volume of water, although volumes will not be high compared to net or pump sampling (e.g., 12 CTD bottles $\times$ 8 − 12 L = 144 L maximum; differences in sample volume should be explored

Table 1. Recommended protocols for microplastics in monitoring programmes. Table modified from AMAP 2021.

Method	Guideline (level)				
	GESAMP 2019 (UN)	Ministry of Environment Japan, Michida et al. 2019 (G20)	BASEMAN 2019 (JPI Oceans project, EU)	Norwegian-Russian Ecosystem survey in the Barents Sea	AMAP 2021 (Arctic Region)
Manta net tow duration and mesh size	Recommended (no details presented)	20 min, 1–3 knots , 0.3 mm	20 min, 1–3 knots	15 min, 2–3 knots, 0.35 mm	10–20 min, 1–3 knots, 0.3 mm *(volume will be variable and depend on sampling conditions)*
Bulk water samples, seawater intake/in situ pump	Feasible (no details presented)	Not considered	Not considered	Feasible	Collected in the subsurface (1–7 m), sequential filtration, e.g., 1 mm, 300 μm, 100 μm
Ferrybox	Not considered	Not considered	Not considered	Not considered	As per bulk water samples
Niskin bottle (CTD rosette)	Not considered	Not considered	Not considered	Possible, volume dependant	Method validation required
Vertical plankton nets	Not considered	Not considered	Not considered	Possible, 200–0 m depth, 180 μm mesh size	Not considered

further). CTD bottles may be combined with bucket sampling to achieve surface and subsurface coverage (Kanhai et al. 2018; Ross et al. 2021); however, further research and methods testing is required to validate the use of CTD rosettes compared to high volume samples.

Sampling programmes conducted on water bodies can be adversely affected by ice, wind and sea state, visibility, tides, plankton blooms, and suspended particulate matter; often requiring calm stable conditions where nets or visual surveys are employed. Access to larger research vessels or ships of opportunity becomes necessary the further offshore (or into the harsh Arctic environment) a monitoring programme extends. Conversely, the use of small craft inshore may limit the size of monitoring equipment onboard and therefore the potential sample size achievable. One limitation of water sampling is the ship's own pollution imprint. Care should be taken to avoid contamination of samples from ship paint and microplastic particles that are blown from the ship into the water, especially if the ship is on station for an extended period. This source of contamination can be mitigated by sampling surface waters immediately upon arrival on station and by deploying surface trawls at an angle and distance to avoid the ship's plume. Bulk-water sampling from other platforms such as ice floes could also help to avoid this source of contamination. The monitoring of water reservoirs will require field methods which do not degrade the quality of drinking water and may have to rely on jar or bucket sampling.

3.2. Water column samples

CTD rosettes can be used to collect water samples at depths impractical for net sampling but may not be able to achieve large sample volumes (e.g., Kanhai et al. 2018). The required sample volume depends on the concentration of anthropogenic and organic material in the sample. Prior studies indicate a sample of 1 m^3 may be appropriate for underway pump sampling in the Arctic (Lusher et al. 2015; Kanhai et al. 2018). Vertical nets used for sampling zooplankton from the water column can also be used to sample microplastics, but attention is required in the volume estimates. For example, if we deploy a net with an opening area of 0.25 m^2 from a depth of 200 m a sampled volume of 50 m^3 could be expected. We suppose that the net's mouth will encounter 0.25 m^3 of water per linear metre of depth and assuming a 200 m depth cast, this will theoretically equal 50 m^3 of water filtered. However, the bow wave effect of the net, which depends on the vertical recovering speed, mesh size, and filtering efficiency, reduces the quantity of water entering the net and the actual volume is less than the geometric volume. A flow meter or an accurate control on the net performance is required to estimate the real water flow across the net's mouth in vertical profiles, as much as it is for horizontal towing. Similarly, multi-nets could be employed to sample the water column at different depths (e.g., Kooi et al. 2016; Lenaker et al. 2019; Egger et al. 2020). These methods require further validation before application in monitoring programmes for microplastics. Large volume pumps attached to the CTD wire have been used in parallel to CTD casts to sample microplastics at different depth strata throughout the water column, but are costly. They facilitate filtration of large volumes of seawater in situ with a low risk of contamination, which give representative results that can be combined with ancillary data obtained from CTD casts (e.g., salinity, chlorophyll *a*, temperature, organic carbon, and nutrients) (Tekman et al. 2020).

Sampling from smaller boats closer to the coast can preferably be carried out using a submerged filter holder with sequential filters and an onboard pump driven by an electrical aggregate. Large volumes of water can be sampled from the sea surface down to 15–20 m depth. The filter holder should be deployed upstream against the current and sampling should be carried out with the engine off (Noren and

Naustvoll 2011; Granberg et al. 2019). Another approach could be to sample water for microplastic analyses along pre-set vertical or horizontal paths of autonomously operated vehicles (AUVs) which would allow assessments along specific sub-mesoscale features such as fronts or the marginal ice zone (Wulff et al. 2016; Choy et al. 2019; Tippenhauer et al. 2021) and avoid the research vessel footprint. Sample replication will be vital for the robustness of this approach in accounting for variation in the sample medium, thus further research and development is required before AUV techniques can be recommended for monitoring microplastics.

3.3. Strengths and limitations of water sampling

It is recommended that the priority for monitoring in the Arctic should focus on surface net samples in all coastal, fjord, and freshwater water bodies or by way of large volume pumps in selected offshore locations (Table 2). Further research activities should subsequently focus on optimising approaches for offshore net samples and pump samples in coastal areas. Before programmes are initiated, it will be necessary for any monitoring programmes to undertake a power analysis per location to assess the variability of plastic concentrations and obstructing factors in a particular region (e.g., algae blooms and high biomass) giving heed to the seasonality of the site to be sampled. Horizontal nets are currently not recommended for offshore sampling as the sampling conditions often hinder a net's ability to collect representative samples (i.e., jumping out on waves and high plankton biomass reducing sampling capacity), although in calm conditions they are not discouraged. As already mentioned, the inclusion of fibres must be carefully considered as there is a high likelihood of cross-contaminating samples if nets cannot be sufficiently cleaned between samples. Similarly, pump sampling in areas with high biomass or suspended particulate matter, such as coastal zones, can complicate the processing of samples, limiting the efficiency of inshore sample campaigns. This can, however, be circumvented by sampling during seasons/times when plankton blooms are not as extensive, assuming the plankton bloom period is not of interest to the monitoring programme.

The sample volumes collected during surveys will be heavily dependent on the sampling conditions. To account for this, the reporting of ancillary metadata is of utmost importance to allow for microplastic data to be normalised for wave and wind speed. When using this approach, data collected from different regions, following the same reporting system, will be comparable. Long-term, ship based, monitoring of the water column (e.g., temperature, salinity, and nutrient concentrations) is well established. Microplastic studies can be seamlessly integrated into existing programmes using shipboard pumps or Ferrybox systems (e.g., Lusher et al. 2015; Yakushev et al. 2021).

Station metadata will then also be available for the environmental contextualisation of microplastic results (e.g., quantifying water stratification impacts on microplastic distribution and transport). Sinking particles or the vertical flux of microplastics can be assessed using moored sediment traps such as those deployed annually year-round at HAUSGARTEN observatory (Lalande et al. 2016). However, determining the direction of microplastic transport within the water column (i.e., sinking and rising, lateral transport) remains a challenge with currently available technology, although systems such as the marine snow catcher or camera systems that are currently in use to study the carbon pump could be adapted to this purpose (van der Jagt et al. 2020). What is achievable in the near-term is comparable concentration data sets as a result of the common adoption of sampling nets and pump systems in microplastics studies globally.

4. Recommended methods for sampling aquatic and shoreline sediment in the Arctic

Microplastics in shoreline and aquatic sediment have been subject to assessment by many researchers around the world. Extensive existing transferable knowledge from other sediment monitoring approaches is available and relevant when investigating the temporal trends of microplastic deposition. The primary approaches are (1) sampling recent surficial sediment deposits at a station recurrently and (2) sampling the accumulated sediment record deposited at a site by the collection of discrete subsurface sediment strata in addition to recent surface deposits. These sediment layers can frequently be dated using radionuclide techniques in undisturbed settings, often with support from other environmental proxies (Martin et al. 2022). Current knowledge and available methods for microplastic assessment are weighted towards surface sediment sampling and can be used to develop monitoring programmes in the first instance. It should be kept in mind that deposition rates vary tremendously between sites and settings, such that the top 5 cm sampled from different areas can be of very different ages and may strictly speaking not be comparable. For example, deposition rates at river mouths or estuaries are very high, such that the top 5 cm contain particles from recent years whereas those from oligotrophic mid-ocean sites can encompass decades to centuries, which impacts the microplastic concentrations deduced. Sampling of the dated sediment record allows for the construction of time series. However, it can be technically challenging to sample at sufficient temporal resolution at deep-sea sites with very low deposition rates, in areas with extreme sedimentation such as below glaciers (Svendsen et al. 2002; Husum et al. 2019), or in areas that have heavily disturbed sediments (e.g., bioturbated from burying and excavation by sediment associated fauna) (Martin et al. 2022).

Concerning shoreline and intertidal sediment, GESAMP (2019) has developed guidelines for the monitoring of microplastics. Applying these methods in the Arctic region is recommended, with consideration of how to adapt to snow and ice conditions. The methodological difference between assessing microplastic content in underwater and shoreline sediment mainly concerns sample collection, whilst processing utilises similar approaches.

If the number of microplastics is expected to be low, the sample size (volume of sediment collected) must be larger.

Table 2. Summary of monitoring and research recommendations for microplastics in water samples. Modified from AMAP 2021.

	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 condition. Large volume pump samples (selected offshore locations, sequential filtration, e.g., 1 mm, 300 μm, 100 μm) collected in subsurface (1–7 m), 1 m^3 per sample. Analysis of polymer ID performed on a selection of representative microlitter particles ≥ 300 μm	Large volume pump samples (sequential filtration down to 10 μm in area of interest) collected subsurface (1–7 m), 1 m^3 per sample
Research	Offshore net samples	Large volume pump samples collected inshore, 1 m^3 per sample from surface waters. Method development into targeting smaller sized particles < 100 μm for routine analysis

Pooling of samples can be used to increase sediment volumes and reduce the influence of sediment heterogeneity (or patchiness), provided they are collected within the same area (and same sampling campaign). There are, however, time constraints when sampling at great depths, where each deployment can take hours. The target size of particles will add a further complication to the volume of sediment required for each sample. The number of particles in a given sample generally decreases with increasing particle size, meaning, for example, that there will typically be many more 10 μm particles than 300 μm particles in a sediment sample (e.g., Bergmann et al. 2017). To obtain representative and meaningful data above the limit of detection, samples targeting the larger-sized fraction (>300 μm) must be larger, and generally exceed 500 g ww (Magnusson, K. personal observations). Each monitoring programme should determine an appropriate sample volume, for example, by power analysis. In all cases, surface sediment should be collected using a metal device rinsed in filtered water and transferred to pre-rinsed non-plastic containers. Sample depth, surface area covered, dry weight, and volume should be recorded. If different sediment depths are obtained, these should be stored separately. Processing should follow recommended procedures (see Supplementary Information for further details).

In addition to the sediment sample microlitter data and methods of sample treatment and plastic extraction, the following parameters should be recorded; when and where (GPS coordinates) the sample was collected, collection method used (type of sampler/equipment), sampling depth, sample size (g ww), total number of collected samples and whether samples were pooled, storage after sampling (AMAP 2021). Any relevant information regarding the nature of the sampled sea bed sediment should also be measured and recorded, i.e., particle size distribution (granulometry), dry weight/wet weight relationship, organic matter content, any available data on biota present, bioturbation depth, and vicinity to potential microlitter sources (JRC 2013; AMAP 2021).

Regardless of procedural choices, all methods, and raw data (including sample volumes/weights) should be reported to facilitate interstudy comparisons and for greater transparency in illuminating study robustness. As previously mentioned, sample sizes can have a significant impact on microplastic concentration data and end users should be aware of the extent of any upscaling of concentration data, which may have been performed to conform to a standardised unit of measure (e.g., environmental samples of a few grams subsequently being reported on as microplastic concentrations per kg).

4.1. Aquatic sediment

There are a variety of different approaches which can be used to collect submerged sediment. It is important that the device used, either box or cylindrical corer, can collect sediment samples whilst keeping an intact undisturbed sediment surface or that a homogenised surface layer is collected, as in the case of grab samples. The gear should be lowered at very low speed when approaching the water sediment interface such that the coring device does not create a bow wave, which washes surficial sediment to the side together with the most recently deposited microplastics. This could result in an unrepresentative sample, especially for grabs and box corers. The most important aspect to achieve a representative sediment sample, regardless of equipment, is practical experience with sediment sampling. The number of grabs or core samples required to achieve a sound statistical dataset for a given sample station, or region, will depend on the level of contamination and the patchiness or heterogeneity of the sediment, and the sampled volume. Low levels of pollution and high patchiness will lead to great variation in numbers of microplastics retrieved. Indeed, bottom currents can swirl sediment and microplastics into depressions on the seafloor, which then become hotspots for microplastic contamination (Kane et al. 2020).

While the continental margins and basins of the Arctic are typically constrained to annual sedimentation rates at the millimetre scale, deposition at the coast can range widely, with annual sediment accumulation varying from millimetres to several centimetres across a single fjord, especially when approaching glacier fronts (Kuzyk et al. 2013; Herbert et al. 2021). It is important to note that as microplastics cannot be readily removed from the environment by clean-up operations, accumulation surveys on microlitter will not entail an initial removal step to zero pollutants, as may be the case with some macroplastic surveys (GESAMP 2019). This may limit the resolvable timeframe of microplastic loading (*depo-*

sition (input) minus resuspension (export)) in sediment to the annual sediment accumulation rate at a site or that monitoring efforts will reflect the total standing stock of microplastics at the time of sampling rather than the accumulation rate. Therefore, an incongruence in the period examined between sediment and overlying water should be expected in monitoring programmes assessing both environments. This also limits the practical resolution (months, seasons, and years) in which a microplastic sediment monitoring programme can be operated in areas without extensive sedimentation or sediment reworking (e.g., beaches). Even restriction of sediment sampling to the upper 1 cm of the sediment column may result in multi-year accumulation records (Paetzel and Schrader 2003; Collard et al. 2021; Loughlin et al. 2021), except for a few areas with high sedimentation (e.g., near glacier fronts) (Stein et al. 2003; Stein 2008; Herbert et al. 2021). Grab sampling can be appropriate at sites of high sedimentation or at heavily bioturbated sites if the sediment surface is clearly distinguishable. In areas of very low sedimentation, surficial sediment may capture the total history of microplastic deposition at a site (Martin et al. 2017; Clayer et al. 2021). Routine monitoring for other pollutants (i.e., organic contaminants and metals) has been successfully carried out for recent marine sediment deposits. Therefore, there is a sound basis for extending this work to assessing the standing stock of microplastics in aquatic Arctic sediment, with the incorporation of water monitoring to evaluate shorter time scales. Even though water and sediment concentrations are not strictly comparable given the aforementioned differences between these environmental compartments.

The deposition rate and the mixing depth of microplastics into sediment are affected by not only natural factors such as ocean currents and bioturbation but also by anthropogenic activities, e.g., trawling, dredging, and other physical disturbances resulting in resuspension events (Martin et al. 2022). In the Arctic additional factors such as sea ice conditions and glacial meltwater impact sedimentation. It is critical that the depositional environment of a monitoring station be characterised, and appropriate sampling strategies and monitoring objectives developed based on site conditions. This may entail a review of previous work in a region or require that the depositional environment of a station be reconstructed from core records or sediment trap data before the commencement of routine sampling as part of a monitoring programme (Harris 2020).

4.2. Shoreline sediment

Shoreline geography can vary from wide mud flats to steep rocky shores, which may be covered by ice and snow or be frozen. Many of the methods for monitoring microplastics on sandy beaches or mudflats are not suitable for broken coastlines with mixed substrates (McWilliams et al. 2018; GESAMP 2019). Furthermore, the geomorphology of the shoreline will strongly influence the distribution of microplastics, where microplastics generally accumulate in sediments closer to the shore, especially on beaches, in fjords, and in estuaries following the general sedimentation patterns of organic matter and small mineral particles (Harris 2020). Obstacles facing this line of research include sampling on high energy rocky shores and the identification of areas of sedimentation modified by coastal marine flora in marshes (which may be less pronounced in Arctic tundra settings). The sampling of litter trapping interstitial spaces on high energy rocky shores is an example of one way to overcome the investigative obstacles imposed by these environments (GESAMP 2019). Most shoreline and beach sediments are sampled using a transect at discrete sampling intervals perpendicular to the waterline. In many cases, this equates to a 1 m^2 sampling quadrat from which the uppermost 5 cm of sediment are retrieved for microplastic analysis (GESAMP 2019; Marine Strategy Framework Directive (MSFD) Technical Subgroup on Marine litter 2020). With the obersvatons that microplastics were buried deeper around rocks on Arctic beaches (McWilliams et al. 2018) and can be buried down to 2 m on sandy beaches (Turra et al. 2014), a modified sampling strategy may be useful. Stratified depth sampling on beaches (e.g., samples every 5 cm) is a possible approach, although it is currently unclear how depth distributions of microplastics on beaches should be interpreted. We currently also lack methods to sample frozen sediments or permafrost, which may accumulate microplastics from precipitated from the atmosphere (Chen et al. 2021).

Because of the patchy distribution of microplastics and microlitter in and on shorelines, and within beach sediment, replication is essential. The Marine Strategy Framework Directive (MSFD) recommendations suggest five replicates (Marine Strategy Framework Directive (MSFD) Technical Subgroup on Marine litter 2020), although there has yet to be any robust statistical validation to assess variability, e.g., via a pilot study aiming to optimise statistical power to determine an appropriate number of replicates. It can also be expected that the required sample size to be above the limit of detection will face similar constraints as those of aquatic sediment.

4.3. Strengths and limitations of sediment sampling

Sediments are highly suitable for monitoring microplastics 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). Whether the objective of a monitoring programme is to follow temporal trends or to target specific sources of microplastic pollution in aquatic sediment, it is essential that sampling be carried out at locations where microplastic settle and accumulate rather than in dynamic areas with strong turbulence, sediment erosion, or transportation. Our knowledge regarding microplastic fate processes and Arctic bottom hydrography and topography is still limited, which makes it difficult to currently identify locations of microplastic accumulation. Certain features such as depressions may become hotspots of microplastics, which can coincide with biodiversity hotspots (Kane et al. 2020).

Patchiness in microplastic sediment concentrations require investigation into the hydrodynamics of an area to identify potential accumulation zones. Because of the lack of established methodology, it is not possible to advise on the monitoring of microplastics < 300 μm (Table 3). This lower

Table 3. Summary of monitoring and research recommendations for aquatic and shoreline sediment samples. Modified from AMAP 2021.

	1st level (must do)	2nd level (should do)
Monitoring	Quantification of microlitter and microplastics (300 μm – 1mm and 1 mm – 5 mm) in surface sediment and accumulation bottoms samples taken by corer or grab.	Point source studies
	Analysis on polymer ID of a selection of representative microlitter particles ≥300 μm.	Visual analysis and polymer ID of microlitter particles ≥100 μm.
Research	Strategies for sampling shoreline and beach sediment for microlitter analysis.	
	Automated analysis on polymer ID of microlitter <100 μm.	
	Determination of deposition areas and microlitter fate processes.	
	Mass-based units for microlitter contents.	

size limit is thus not based on ecological or ecotoxicological relevance. There is a great need to be able to routinely sample much smaller microplastics and even nanoplastic fractions.

Some studies show correlation between microplastic concentrations and sediment grain size and (or) organic matter content (Strand et al. 2013; Vianello et al. 2013; Enders et al. 2019; Gomiero 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) concluded that intertidal sediment generally contained higher microplastic concentrations. Still, some of the highest concentrations of microplastics recorded in marine sediment were found in the deep sea at the Fram Strait and west Canadian Arctic (up to 130 000 and 16 000 microplastics kg^{-1} sediment; Huntington et al. 2020; Tekman et al. 2020), supporting the theory that deep-sea sediments are a sink for microplastics (Woodall et al. 2014). In general, particles of various kinds, i.e., phytodetritus, zooplankton faecal pellets, lithogenic material, and fine-grained mineral particles, settle in calm areas and form soft-sediment bottoms. This is where organic matter and sediment-associated contaminants accumulate and are generally monitored. It is likely that microplastics settle in a similar way given their physical characteristics (Harris 2020). Microplastics may also be incorporated in marine aggregates which are mainly formed by algae and detritus (Porter et al. 2018; Zhao et al. 2018; de Haan et al. 2019) and could be supported by the sticky extrapolymeric substances generated by (ice) algae (Peeken et al. 2018; Hoffmann et al. 2020). These aggregates, often referred to as marine snow, have faster sinking velocities than individual particles and could be important vehicles for the transportation of small particles from the water surface to the seafloor (Boetius et al. 2013).

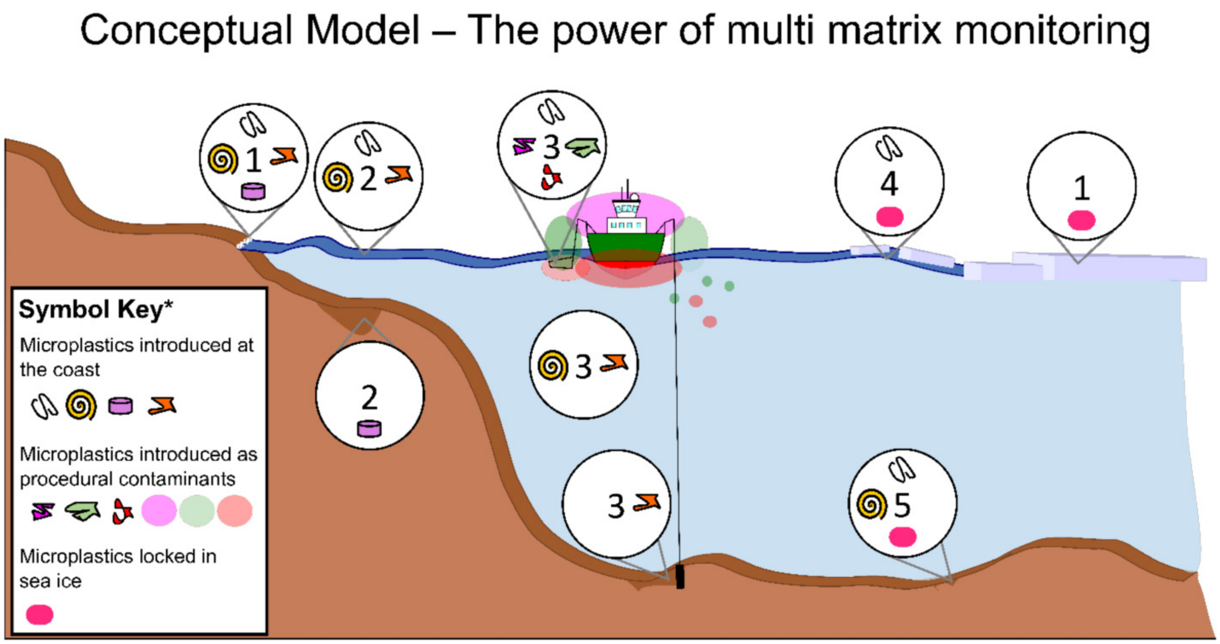
Finding a representative location for monitoring microplastics requires either pre-existing knowledge and (or) an initial screening of an area, preferably supported by hydrodynamic modelling to target areas where particles are likely to settle. Marine sediments are characterised by a highly heterogeneous composition and abundance of benthic fauna. This results in a high degree of spatial and temporal variability. Video-guided coring can help to avoid sites with obvious bioturbation or stones (Bergmann et al. 2017).

One aspect of designing a sediment programme that must not be overlooked is cost and logistics. Whilst shoreline sediment and beaches offer relatively easy access and cost-effective options for microplastic assessments, they may be complicated by the geology of the shoreline and require transport by boat or helicopter and must be accompanied by a bear watch. On the other hand, benthic sediment sampling demands high costs due to access to equipment and the ship time needed for field work. Ice conditions may also impede sampling both on and offshore.

5. The value of water and sediment monitoring

It is recommended that monitoring programmes consider a joint water and sediment approach. The rationale for this is that water and sediment sampling can often be carried out in the same sampling campaign and provide complementary, but not overlapping, information on the status, and trends of plastic pollution. When water and sediment sampling are combined, they provide the most complete picture of microplastic pollution of marine and freshwater environments (Fig. 2). This includes any potential organism exposure risk, from benthic to pelagic realms. Furthermore, water and sediment sampling provide different spatial and temporal perspectives on plastic pollution. Sediment provides a more spatially and temporally integrated signal of plastic contamination, whereas water samples can possibly track more rapid fluctuations such as what might occur with increased shipping in the Arctic or if communities alter their wastewater treatment processes. However, capturing the target water mass can be challenging, thus hydrodynamic processes in the area need to be well known to interpret results. It is also important to note that although plastics in the sediment have moved through the water column, it is difficult to draw a direct relationship between plastic concentration and composition in the water and in sediment, and that 1:1 compar-

Fig. 2. Illustration of a potential benthic-pelagic microplastics pathway. **1.** Initially a series of microplastics are released at the coast (left) and legacy microplastic pollution is trapped in sea ice (right). **2.** Next dense microplastics settle rapidly in the estuary and are quickly buried in a high sedimentation area, while others are carried in coastal currents. **3.** Researchers operate within an area affected by their own microplastic shedding. At the surface floating microplastics from the shore are collected along with microplastics generated from the research cruise. Other microplastics are carried long distances by water masses as they sink. Still other microplastics are carried by bottom currents or debris flows and settle on the shelf, abyss, or in depressions. **4.** Microplastics mix and sink at the ice margin, released from the ice or carried by northerly currents and ships. **5.** Accumulation of variously sourced microplastics offshore. Symbols are used here to represent microplastics as a diverse suite of pollutants (morphologies, polymers, colours, etc.) and to illustrate potential pathways for individual particles. This is not a representation of specific types of microplastics found in the environment nor of the expected relative concentration levels or assemblages of microplastics found in individual environmental compartments.



ison of water and sediment by volume is invalid or misleading (Graf 1992). Source proximal sampling is always advisable and most cost efficient, e.g., monitoring wastewater at the source rather than trying to track it in various compartments of the recipient (von Friesen et al. 2020).

There are few examples, either from the Arctic or globally, of studies that have examined both water and sediment in a joint research programme or analysed this type of data in a multivariate way. It is critical to understand the interaction between water bodies and sediment when considering the transport and fate of microplastics in the aquatic environment. For example, when collecting water and sediment samples - upstream and downstream of a dam in New York state in the USA, Watkins et al. (2019) found that sediment in the reservoir behind the dam structure may be a sink for fragments and other plastic morphologies besides microfibers at long timescales. An even more comprehensive approach to plastic pollution monitoring is demonstrated by Courtene-Jones et al. (2021). This study in the Caribbean sampled marine (surface water, subsurface water, and sediment) as well as terrestrial litter to explore the origin, transport, and fate of plastic pollution in the study region. Their findings show that both local and distant sources resulted in plastic pollution in the marine samples and illustrate how sampling multiple environmental compartments can be used to understand potential transboundary patterns, and thus policy needs. A series of studies along the coastline in South Africa, using surface waters and shoreline sediment, demonstrated that proximity to land-based sources were less likely an influence on microplastic concentrations than water circulation (Nel and Froneman 2015; Nel et al. 2017), although samples taken directly in two harbours had much higher levels of microplastics, suggesting that harbours may be a local source and should be studied in more detail (Nel et al. 2017). It should be noted that there are other papers that examine water and sediment in the same region, but these lack a multi-matrix comparison (Lorenz et al. 2019; Mu et al. 2019a; 2019b; Mintenig et al. 2020; Pan et al. 2021).

There are three published studies from the Arctic that use a multi-matrix approach. Hamilton et al. (2021) sampled and analysed surface water and shoreline sediment samples from the same region on the eastern coast of Baffin Island. These concurrent samples showed similarities in the sizes and colour of microplastics, but significantly differed in their shape (more fragments in the water samples versus more fibres in the shoreline sediment) and their material type (surface water samples were dominated by paint-derived particles, whereas shoreline sediments were dominated by cellulosic particles). These results suggest that these two different matrices are being influenced by different microplastic sources. It is also important to note that while the sources could be the same, the fate of microplastics likely varies by shape and size, and thus different concentrations may be present in different matrices. Huntington et al. (2020) examined microplastic in surface water, zooplankton, sediment, and snow samples from the eastern Canadian Arctic waters of Nunavut. Microplastics were found to be prevalent in surface water, zooplankton, and sediment, while snow samples were found to be of insufficient volume for an analysis of regional microplastic concentrations. Tekman et al. (2020) examined microplastics concurrently in benthic sediment, the water column, and surface samples from the HAUSGARTEN observatory in the Fram Strait. This study found that microplastic concentrations were present throughout the water column but were highest in the sediment samples at each of the five stations examined, as was the number of polymer types and size classes present. The authors attribute these differences again to how microplastics accumulate in these matrices: all water samples represent a snapshot in time, whereas sediment samples reflect microplastic accumulation over longer time scales. The represented timeframe being dependent on the sedimentation rate and depth of sampling.

As there has been a lack of systematic monitoring of microplastics, in all settings, our understanding of environmental loading of microplastics is largely derived from top-down estimations of plastic loss from supply chain production and usage data (Bancone et al. 2020). As such, our knowledge of microplastic movement through the environment is limited and largely based around modelling scenarios with what ground truthing from case studies has been made available. Water and sediment matrices are drastically different environments and evidence suggests that they are undergoing very different patterns of microplastic pollution. Active monitoring of transfer zones (water and energetic environments) and longer-term depositional settings (aquatic sediment in accumulation areas) enhances a monitoring programme's ability to capture a complete pollution profile of a setting and prevent important individual ecosystems from being overlooked. Potential scenarios to consider include: an erosional sedimentary environment that may have limited microplastic pollution while the overlaying waters could still contain significant microplastic inventories, affecting plankton and nekton. Conversely, rapid sinking of microplastics could impact the benthos, while leaving the overlaying waters to appear relatively pristine in a monitoring survey. Indeed, modelling the two-dimensional trajectories of microplastics detected in the Fram Strait showed that many of the particles were delivered by lateral advection processes (Tekman et al. 2020). Also, water masses of different origin may prevail at different depths, e.g., in the eastern Fram Strait, Atlantic waters prevail at the top 300 m of the water column and cold polar water underneath including above the seafloor (Tekman et al. 2020), resulting in different source areas for microplastics. It is entirely possible that microplastics may be sorted in a setting by density and morphology creating distinct pollution profiles on either side of the water sediment interface. The separate loading inventories for these two matrices will then be defined by the types of plastics being sourced to a setting and their residency time in either ecosystem. Untangling these issues of residency time and source-to-sink processes will require the multi-scale multi-matrices monitoring approach recommended here (Fig. 2).

6. Opportunities for future microplastic monitoring in the Arctic

6.1. Existing water and sediment sampling programmes are already in place for other purposes in the Arctic

There have been several sporadic scientific investigations of microplastics in the Arctic (see the Supplementary Information), with few attempts of including microplastics in sampling programmes. Linking microplastic sampling to already existing monitoring programmes is advantageous because other ancillary parameters relevant for microplastic monitoring will be measured at the same time, e.g., sediment granulometry and organic matter content. Such efforts have already begun in Norwegian waters with the introduction of microplastic assessments under the programmes: Økokyst (Ecosystem monitoring of Coastal Waters: Barents Sea, Norwegian Sea North), Milkys (Contaminants in coastal waters of Norway), and Havforsuringsprogrammet (Monitoring ocean acidification in Norwegian seas), coordinated by the Norwegian Institute for Water Research on behalf of the Norwegian Environment Agency, and the Barents Sea ecosystem survey, coordinated by Institute of Marine Research, Norway in collaboration with Polar branch of the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO) and Nicolai M. Knipovich Polar Research Institute of Marine Fisheries and Oceanography (PINRO) in Russia. Similarly, the Norwegian monitoring programme, Mareano, could be suitable for monitoring microplastics in Arctic marine sediment as it covers the northern Norwegian coastal and offshore areas including the Barents Sea; and preliminary studies are being undertaken (Jensen and Cramer 2018). Another example is HAUSGARTEN, the deep-sea observatory in the Fram Strait, operated by The Alfred Wegner Institute Helmholtz Centre for Polar and Marine Research (AWI). Here, sediments are sampled for various scientific purposes including litter and microplastic pollution. Still, there is a bias in the above-mentioned programmes as they are focused on the marine environment. This matches the inclusion of plastic monitoring under the EU Marine Strategy Framework Directive (MSFD) but absence from the Water Framework Directive (WFD). Nevertheless, with the copious amount of data emerging on plastics in freshwater and terrestrial systems, they should not be overlooked. Especially given that this environment is often related to sources or releases of microplastics, and mitigation efforts should aim to be linked as close to sources of release as possible.

Important for implementation of microplastic monitoring in the Arctic are examples of water and sediment sampling for microplastics being undertaken by both community members and via dedicated research stations. Paradinas et al.

(2021) outline and test protocols using citizen science to collect water and shoreline sediment samples to examine geographic patterns in microplastics. Engaging the established and expanding Arctic communities in this process could provide an avenue for overcoming the logistical challenges of establishing Arctic microplastic monitoring in often remote locations.

6.2. Target areas for microplastic monitoring in water and sediment

Fjords represent a coastal interface between, terrestrial, marine, atmospheric, and cryosphere processes (e.g., Wlodarska-Kowalczuk and Pearson 2004). While this creates a complicated environment for resolving microplastic transport influences, with careful interpretation the opportunity exists to evaluate multiple important Arctic source-to-sink vectors for microplastic pollution in these settings. Fjords serve as the world's most efficient geomorphological features for carbon capture (Bianchi et al. 2020) and Harris (2020) places fjord environments as also having the highest potential and observed rates of microplastic sediment deposition in marine settings. Therefore, these are sensitive environments highly suitable for microplastic monitoring programmes. The natural geography of fjords has long been held as ideal for settlement and port facilities (Syvitski et al. 2012). Many fjords have been urbanised and this trend can be expected to continue with increasing arctic settlement. It can then be expected that local sourcing, in addition to long range transport, will be important factors contributing to the microplastic pollution of fjords (e.g., von Friesen et al. 2020; Liborion et al. 2021). Fjord harbours also provide the infrastructure and coastal protection needed for launching efficient monitoring initiatives and therefore should be an early target of monitoring programmes. The Northern Fjord Belt extending above the 43rd parallel is a bellwether for modern earth processes at high latitudes, producing exceptional natural sediment archives, exploitable for microplastics monitoring (Syvitski et al. 2012; Bianchi et al. 2020).

The redistribution and accumulation of litter and microplastics in the environment, including in the Arctic, are affected by the general atmospheric and oceanic circulation patterns. Modelling the movement and fate of litter and microplastics can help us to better understand, and eventually address, their sources, presence, and impacts. Modelling the flow of litter and microplastics into the Arctic has the potential to help identify and quantify sources, whereas modelling the movement and fate of these materials within the Arctic can help identify geographic areas of interest and litter types. Modelling litter and microplastics 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. Therefore, microplastics and litter data from surface waters and within the water column are needed for such modelling efforts. Although scarce, data collected from the water column (marine or freshwater) do exist (Amélineau et al. 2016; Kanhai et al. 2018; Tekman et al. 2020; von Friesen et al. 2020). Such data on the presence of microplastics in the Arctic water column support the hypothesis that the water column constitutes a major reservoir for microplastics (Cózar et al. 2017). However, plastic litter is a diverse class of pollution, different plastics have varying properties in terms of size, shapes, and buoyancy, and are thus much more difficult to model with existing applications (van Sebille et al. 2020).

There is also a lack of modelling for freshwater inputs of litter and microplastics into the Arctic region. Freshwater inputs of litter and microplastics to the Arctic remain unknown, and pathways for litter and microplastics from oceanic and freshwater sources are needed to ensure that 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 modelling 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 microplastic concentrations in northern rivers (e.g., Yakushev et al. 2021; Frank et al. 2021) (or in freshwater ecosystems in general), and on how these systems may be acting as conduits for microplastic pollution to northern marine environments. Therefore, to add to our understanding of freshwater sources, sinks, and the circulation of litter microplastics, projects focused on monitoring within watersheds and water bodies flowing into the Arctic should be prioritised.

6.3. Monitoring with, by, and for Arctic Peoples

These recommendations are based on the priorities and insights of an international scientific community. However, this does not mean they include the research needs and priorities of communities and Indigenous peoples in the Arctic, and some of the methods, categories, standards, and research questions in plastic pollution research in the Arctic are skewed towards southern understandings and landscapes, as discussed above (Liboiron at al. 2021; Melvin et al. 2021). The Inuit Tapiriit Kanatami (ITK), an organisation representing the 65 000 Inuit in the Canadian Arctic (Inuit Nunangat), has written in its National Inuit Strategy for Research that, "for far too long, researchers have enjoyed great privilege as they have passed through our communities and homeland, using public or academic funding to answer their own questions about our environment, wildlife, and people. Many of these same researchers then ignore Inuit in creating the outcomes of their work for the advancement of their careers, their research institutions, or their governments. This type of exploitative relationship must end" (Inuit Tapiriit Kanatami 2018: 3). ITK recommend five priority areas for research in their homelands, including: advancing Inuit governance in research, including being part of funding decisions; enhancing the ethical conduct of research, including strong community partnerships; ensuring Inuit access, ownership, and control over data and information gathered in their homelands, including monitoring data; and building capacity in Inuit research through skill-sharing, equal partnership, and research infrastructure (Inuit Tapiriit Kanatami 2018: 4). While each Indigenous group and community in the Arctic will be different, many of these principles will hold across the Arctic. We recommend that future monitoring research aligns with these principles with an emphasis on the priorities of local and regional Arctic communities.

7. Conclusion

Assessing Arctic ecosystems for litter and plastic pollution is high on the agenda of the AMAP nations. Coordinated efforts by all parties will contribute to a combined knowledge of the distribution and fate of this global pollutant and aid in identifying priority areas/regions where mitigation efforts should be focused. Without baseline data that are comparable across the Arctic region—collected from water bodies and sediment—it becomes far too complicated to compile the data required by policy and researchers who want to model the movement and consequences of plastic pollution. As explained above, the data that are currently available from these environmental compartments are sporadic, collected with different methods and processed with different approaches, generating results that are not currently comparable across the Arctic region. Effort must be directed towards harmonising these approaches and validating the extent to which data can be used in combination. Until then, data generated may only have usability at a local scale. It is essential that the approaches taken by individual parties can come together to produce a harmonised and comparative dataset. Quantifying microplastics in sediment and water from the same region will facilitate a three-dimensional picture of plastics, not only as a snapshot in time, but as an ongoing process of pollution within the Arctic.

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The authors declare there are no competing interests.

Supplementary material

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