Arctic Science

OPEN ACCESS | Review

Microplastics in Arctic invertebrates: status on occurrence and recommendations for future monitoring

Bjørn Einar Grøsvik[a], **Maria E. Granberg**[b], **Tanja Kögel**[a,c], **Amy L. Lusher**[c,d], **Alessio Gomiero**[e], **Halldor P. Halldorsson**[f], **Alexander Klevedal Madsen**[d], **Julia E. Baak**[g], **Hermann Dreki Guls**[f], **and Kerstin Magnusson**[b]

[a]Institute of Marine Research, P.O. Box 1870 Nordnes, Bergen, N-5817, Norway; [b]IVL Swedish Environmental Research Institute, Kristineberg Marine Research Station, Fiskebäckskil, S-45178, Sweden; [c]Department of Biological Sciences, N-5006, University of Bergen, Bergen, Norway; [d]Norwegian Institute for Water Research, N-6273, Oslo, Norway; [e]Department of Climate and Environment, N-5007, Norwegian Research Centre, Stavanger, Norway; [f]University of Iceland's Research Centre in Sudurnes, University of Iceland, Gardvegi 1, 245, Sudurnesjabaer, Iceland; [g]Department of Natural Resource Sciences, McGill University, Sainte Anne-de-Bellevue, QC H9X 3V9, Canada

Corresponding author: **Bjørn Einar Grøsvik** (email: bjorn.grosvik@hi.no)

Abstract

Few studies have been published on the occurrence and distribution of microplastics (MPs) in invertebrates from the Arctic. We still need to develop harmonized methods to enable good comparison between studies taking into account recovery rates, size ranges, shapes, and polymer types. Here, we review studies on MPs in invertebrates from the Arctic and present suggestions on sampling protocols and potential indicator species. Since information on MPs in Arctic invertebrates is vastly lacking, we recommend to at least include suspension feeding bivalves like mussels in monitoring programmes to function as indicator species in the Arctic. Mussels have also been suggested as indicator species for MP monitoring in coastal regions further south. Although we recognize the challenge with particle selection and egestion in mussels as well as the relatively low concentrations of MPs in Arctic waters, uptake levels seem to represent recent exposures. More research is needed to understand these selection processes and how they affect the bioaccumulation processes. Future research should include studies on whether different functional groups of invertebrates have different exposures to MPs, e.g., if there are differences between sessile versus motile species or different feeding strategies. More knowledge on monitoring strategies for pelagic and benthic species is needed.

Key words: Arctic, microplastics, invertebrates, occurrence, monitoring

Résumé

Peu d'études ont été publiées sur la présence et la distribution des microplastiques (MP) chez les invertébrés de l'Arctique. Il est encore nécessaire de développer des méthodes harmonisées pour permettre une bonne comparaison entre les études en tenant compte des taux de récupération, des gammes de tailles, des formes et des types de polymères. Les auteurs examinent ici les études réalisées sur les MP dans les invertébrés de l'Arctique et présentent des suggestions sur les protocoles d'échantillonnage et les espèces indicatrices potentielles. Puisque les informations concernant les MP dans les invertébrés de l'Arctique sont largement insuffisantes, ils recommandent d'inclure au moins les bivalves se nourrissant en suspension, comme les moules, dans les programmes de surveillance afin qu'ils servent d'espèces indicatrices dans l'Arctique. Les moules ont également été suggérées comme espèces indicatrices pour la surveillance des MP dans les régions côtières plus au sud. Bien que l'on reconnaisse le défi que représentent la sélection et l'éjection des particules dans les moules ainsi que les concentrations relativement faibles de MP dans les eaux arctiques, les niveaux d'absorption semblent représenter des expositions récentes. Des recherches supplémentaires sont nécessaires pour comprendre ces processus de sélection et la façon dont ils affectent les processus de bioaccumulation. Les recherches futures devraient inclure des études visant à déterminer si les différents groupes fonctionnels d'invertébrés sont exposés différemment aux MP, par exemple, s'il existe des différences entre les espèces sessiles et les espèces mobiles ou selon des stratégies d'alimentation différentes. Des connaissances supplémentaires sur les stratégies de surveillance des espèces pélagiques et benthiques sont requises. [Traduit par la Rédaction]

Mots-clés : Arctique, microplastiques, invertébrés, présence, surveillance

Introduction

Discharges of litter and microplastics (MPs) are of increasing concern to the world oceans. This also includes the Arctic, as litter and MPs have been reported on the seafloor (Buhl-Mortensen and Buhl-Mortensen 2017; Grøsvik et al. 2018), in sea water (Lusher et al. 2015; Tekman et al. 2020; Martin et al. this issue), in sediments (Bergmann et al. 2017; Tekman et al. 2020; Martin et al. this issue), in sea ice (Obbard et al. 2014; Peeken et al. 2018), and in snow (Bergmann et al. 2019). Widespread transport, and occurrence, of litter and MPs in the Arctic also raise concern on how litter and MP pollution may affect the ecosystem. Several reports have documented uptake in stomachs of seabirds (e.g., northern fulmars) (Trevail et al. 2015), in fish (Kögel et al. this issue) but less so for invertebrates. It is important that the methods applied allow for good comparison between studies, preferably using harmonized methods whereby the differences in approaches can be quantified. More knowledge is also needed related to indicator species to obtain better understanding on uptake, regional differences, possible trends, and threshold levels. Such information can also provide indications of ecosystem health and informed advice for the management of possible impacts and results of mitigation efforts.

Coupled to information on how different polymer types, shapes, sizes, and concentrations may affect selected species and life stages in controlled laboratory experiments, environmental concentrations may be used in exposure studies to enable risk assessments (Kögel et al. 2020). Many laboratory studies, however, use unrealistically high exposures (e.g., Setälä et al. 2014; Cole et al. 2013, 2016). This may reflect environmental MPs concentrations when comparing hotspots such as city harbours and estuarine environments but not for remote offshore sites (e.g., Gomiero et al. 2019; Bråte et al. 2020). Furthermore, most laboratory investigations expose organisms with round, emulsion polymerized plastic beads, rather than degradation products—plastic fragments and fibres, which are prevalent in the environment. These studies function as "proof of concept" but have their limitations when deducing the fate and effects of MPs in nature (Phuong et al. 2016). More information is therefore needed on which sizes, shapes, and polymer types can pose problems for invertebrates under realistic exposure situations. Results from field collected animals show that the size of ingested particles varies between species and is distinctly influenced by the size of preferred food items (Desforges et al. 2015; Botterell et al. 2019). This has been verified in an experimental study where it was also observed that species ingested particles in the size of their natural preys, whilst no clear selection related to the shape of the particles could be observed (Lehtiniemi et al. 2018).

Recognizing these shortcomings, it is useful to establish recommended indicator species for different parts of the food web, both from the water column and the benthic fauna for species representative of the Arctic ecosystems. The objectives for this work are to sum up knowledge on uptake and occurrence in pelagic and benthic invertebrate species from the Arctic and advice on sampling and analysing methods and relevant species when planning future MP monitoring in the Arctic.

Summary of information to date

There are only a handful of studies that quantify and characterize ingestion of plastic by Arctic marine invertebrates (reviewed by Collard and Ask 2021). Here, we conducted a literature review to expand upon the results of Collard and Ask (2021). Articles were included if they reported original data of MPs in any invertebrate species. Article types included peer-reviewed journal articles as well as scientific and technical reports. This search resulted in 12 articles and reports discussed by species group below, together with selected findings on these groups on the distribution, uptake, and effects. An overview of invertebrate groups and sample sites within the Arctic is shown in Fig. 1 and Table S1.

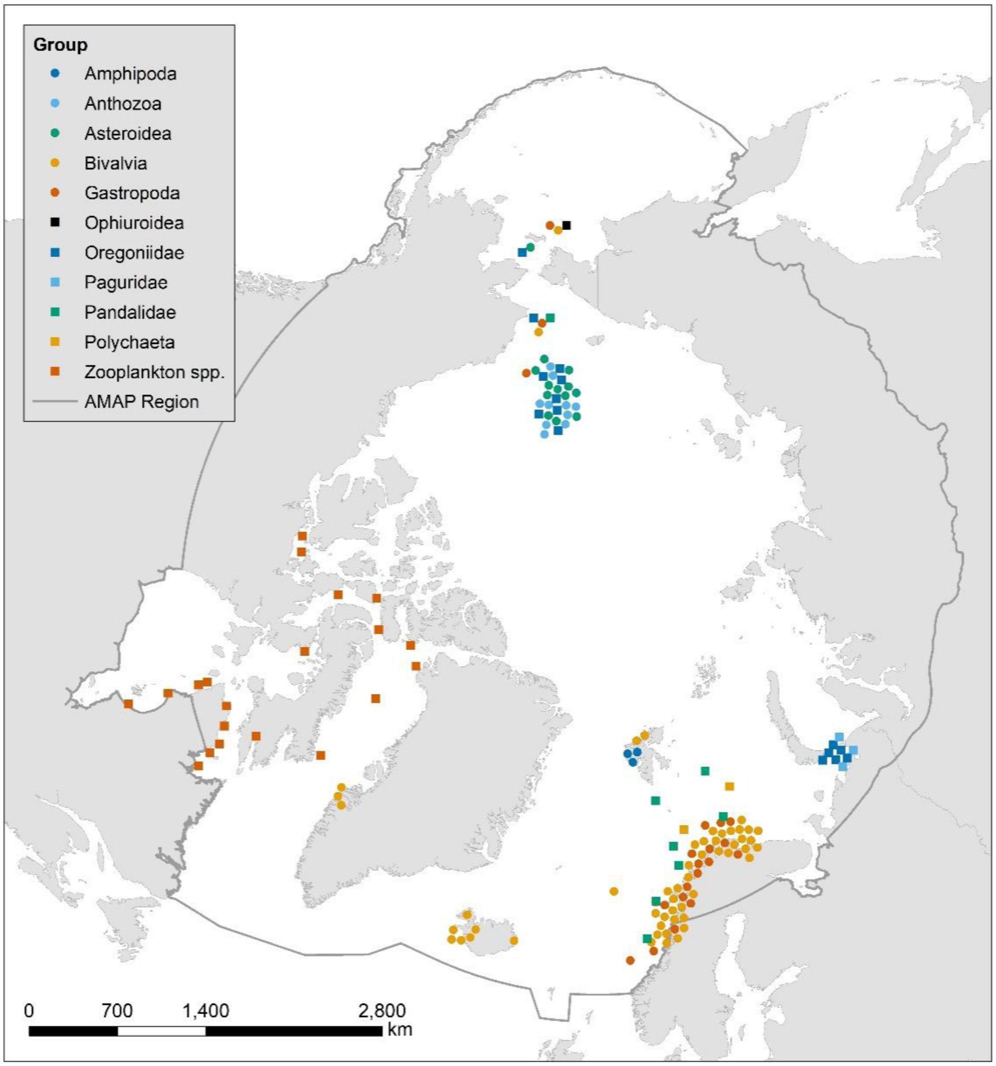
Pelagic invertebrates

The pelagic zone harbours a plethora of planktonic invertebrate species. These organisms show limited mobility, although many show patterns of diel vertical migration, such as copepods. Planktonic invertebrates have different types of feeding habits or life stages and some change life stages or change feeding habits as they develop from larva to juvenile and adult. When feeding, some species are more selectively picking out food items compared to others. Many benthic or sessile invertebrates have pelagic mobile larvae such as various crabs, echinoderms, and molluscs. Important processes connecting the pelagic and benthic realms including the shredding of gelatinous houses (appendicularians), release of exopolymeric substances (EPS), and sinking or sedimentation of faecal matter and dead organisms. These processes function as vectors for the transport of MP from surface to deeper waters and the sea floor.

Crustaceans

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). There are three main calanoid copepod species, *C. finmarchicus*, *C. glacialis*, and *C. hyperboreus* (Berge et al. 2012). The effects of 20 μm polyethylene (PE) spheres on these three species were investigated by Rodríguez-Torres et al. (2020), showing a low impact at environmentally relevant concentration (200 MPs L^{-1}), while observing increased egg production rates at higher concentrations (20 000 MPs L^{-1}). Cole et al. (2019) found that nylon fibres (10 × 30 μm) can affect prey selectivity in *C. finmarchicus* and that both nylon fibres and granules (10–30 μm) caused earlier moulting (50 000 MPs L^{-1}). Laboratory exposures with polystyrene (PS) particles in the size range 1.7–31 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 (PS particles, 20 μm; Cole et al. 2015). Particle concentrations in these two studies were extremely high compared to what is normally found in the environment, 4 × 10^6 and

Fig. 1. Locations of existing sampling for microplastics (MPs) in invertebrates in the Arctic Monitoring and Assessment Programme (AMAP) region.



75 000 MPs L^{-1}, respectively. As an example, water concentrations of MP > 11 μm in the area around the HAUSGARTEN observatory in the Fram strait ranged between 0 and 1.3 MP L^{-1} (Tekman et al. 2020). Vroom et al. (2017) observed that both PS spherical particles (mainly 15 μm, but also 30 μm) and fragments (<30 μm) were ingested by *C. finmarchicus* but did not observe any effects on survival (50 000 and 500 000 MPs L^{-1}). PS particles are widely used in laboratory experiments, although a variety of different polymer types have been observed in field studies. *C. helgolandicus*, a species common to the North Atlantic, has been shown to ingest spheres, fibres, and fragments of different types of polymers (PE, nylon 66, and polyethylene terephthalate; PET) in exposure studies, leading to changes in feeding behaviour and selectivity for feeding on algae (exposure: 100 000 MPs L^{-1}) (Coppock et al. 2019).

Several field studies have shown uptake of MPs in crustacean zooplankton under natural conditions. Two pelagic species, the calanoid copepod *Neocalanus cristatus* and the euphausiid shrimp *Euphausia pacifica*, were analysed for their content of MPs in a field study carried out in the Northeast Pacific Ocean, and the coastal waters of Southeast Alaska and British Columbia (Desforges et al. 2015). In *N. cristatus*, a total of 25 MPs were detected in 960 analysed individuals, and in *E. pacifica* 24 particles in a total of 413 analysed individuals. Reports from regions outside the Arctic also report on low MP concentrations often not surpassing 0.1 particles/individual animal, e.g., from the Southern China Sea (Sun et al. 2017; Amin et al. 2020), Yellow Sea (Sun et al. 2018*a*), East China Sea (Sun et al. 2018*b*), and Bohai Sea (Zheng et al. 2020).

Huntington et al. (2020) reported the presence of MPs in zooplankton from the Eastern Canadian Arctic. The zooplankton samples were collected by trawling and analysed in bulk. In 18 out of 20 samples (∼90%), MPs were observed and the mean abundance was 3.5 ± 4.0 pieces/g wet weight of zooplankton. The concentrations were unrelated to upstream urban populations and were suggested by the authors to be the result of long-range transportation. Recent reports highlight the importance of long-range transport of MPs to the Arctic by ocean currents (Huserbråten et al. 2022) and atmospheric transport and deposition (Evangeliou et al. 2020; Dong et al. 2021) emphasizing the need to understand how this can impact Arctic ecosystems in the future.

Tunicates

Appendicularians are a group of pelagic tunicates with worldwide distribution (Fenaux et al. 1998). Due to their gelatinous filter "house", a structure used to capture and concentrate food from water, these free-swimming tunicates are efficient grazers on pico- and nanoplankton (Vargas and González 2004). Additionally, their production of faecal pellets and house aggregates is important for vertical flux of organic material in the oceans including the Arctic (Acuña et al. 2002; Turner 2015).

Oikopleura vanhoeffeni, *O. labradoriensis*, and *Fritillaria borealis* are three common cold-water appendicularian species that are also found in arctic waters (Choe and Deibel 2008; Deibel et al. 2017; Hop et al. 2019). Uptake of plastic beads in laboratory exposures has been well studied in several appendicularians, including *O. dioica* (Bedo et al. 1993; Fernández et al. 2004; Conley and Sutherland 2017), *F. borealis* (Fernández et al. 2004), *O. vanhoeffini* (Deibel 1988; Deibel and Lee 1992), *Stegasoma magnum* (Alldredge 1981) and the giant larvacean *Bathochordaeus stygius* (Katija et al. 2017). These studies show that appendicularians readily capture and ingest small MP and submicron particles. There is little data on levels of MPs in field-sampled appendicularians, and analysis can be challenging since these organisms have very short intestinal passage times (Fernández et al. 2004) and replace their houses up to several times a day (Deibel 1988). However, analysis of faecal pellets and house aggregates can be a viable method for detection. MPs have, for example, been observed in discarded house aggregates from *Bathochordaeus* spp. in Monterey Bay (California, USA) (Choy et al. 2019). To our knowledge, there are no studies on MPs in tunicates in the Arctic.

Role of zooplankton in transport of microplastics

Marine aggregates can be an important vector, mediating the vertical flux of MPs. Although having been much explored in relation to carbon flux in world oceans, the mechanisms and efficiency of this process in relation to MPs are not well understood (Kvale et al. 2020). MPs have been shown to be captured, ingested, and incorporated into faecal pellets of different species (Cole et al. 2016; Wieczorek et al. 2019), appendicularian houses (Choy et al. 2019), and phytoplankton aggregates (Long et al. 2015; Möhlenkamp et al. 2018). Incorporation of MPs in aggregates can increase the sinking velocity of the particles compared to sinking rates as free particles (Porter et al. 2018). Exposures with very high MP concentrations in laboratory studies have indicated a possible decrease in the sinking speed of the faecal pellets compared to pellets without plastics (Cole et al. 2016; Wieczorek et al. 2019). MP-laden buoyant faecal pellets have, to our knowledge, not been observed in the field. A likely explanation for this is that exposure concentrations are much lower in nature than in the experiments and many other types of particles than MPs are present for selectively feeding zooplankton.

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 mass of natural organic material to which POPs absorb surpasses the plastics and MPs (Koelmans 2015). In a study from the South Atlantic Ocean, several hydrophobic organic contaminants were analysed 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 (Rochman et al. 2014).

The melting zone of the 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 concentrations of MP particles (Obbard et al. 2014; Peeken et al. 2018; von Friesen et al. 2020), ice-associated zooplankton should be targeted when aiming to monitor fate and effects of the sea-ice-associated MP (von Friesen et al. 2020).

Benthic invertebrates

Benthic invertebrates are either sessile (physically attached to one place) or mobile, and live either epibenthically (on the surface) or infaunal (in sediments). They display a range of feeding strategies and feeding modes and many species can switch between them as required. Benthic invertebrates can be filter feeders, benthic deposit feeders, conveyor belt feeders, and predators. They can filter feed with an internal apparatus (e.g., feeding basket) like sessile tunicates (e.g., *Ciona intestinalis*) or by constructing a filtering mucus net like burrowing polychaetes (e.g., *Arenicola marina*). Like pelagic invertebrates, benthic invertebrates may be selective or non-selective feeders. The living and feeding habits (the functional group association) of a species will jointly have a great impact on an organism's exposure to MPs.

MPs sink to the seafloor when the polymers have densities 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), or by 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 MPs 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/g 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, microfibres were the most common MP form found.

Bivalves

Actively filter-feeding species like bivalves have been suggested as candidate sessile and semi-sessile organisms for monitoring the uptake and effects of MP particles in seawater and sediments (GESAMP 2019). Blue mussels (*Mytilus edulis*) have been suggested as a global bioindicator of coastal MP pollution in temperate waters due to their wide distribution, ability to show recent exposures to MPs and tissue response pattern after exposure to high concentrations in laboratory experiments (Li et al. 2019). Mussels have been shown to indicate differences between sites with large differences in MP pollution pressures (Bråte et al. 2018). Although we recognize the challenge with particle selection and egestion in mussels (Woods et al. 2018; Ward et al. 2019), as well as the relatively lower concentrations of MPs in Arctic waters, uptake levels seem to represent recent exposures (Li et al. 2019). More research is needed to understand these selection processes and how they affect the bioaccumulation processes. Until now, mussels are the best harmonized indicator species currently available, with many researchers applying comparable methods (Li et al. 2019; Dehaut et al. 2019).

Several field-collected mussels have been shown to contain MPs (Bråte et al. 2018; von Friesen et al. 2020). Intertidal 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).

Blue mussels are, however, rarely found in the higher Arctic (e.g., Svalbard, Northern Greenland, Canadian Arctic) and "substitution species" with comparable feeding strategies should thus be used, e.g., the Greenland smoothcockle (*Serripes groenlandicus*), or the wrinkled rock-borer (*Hiatella arctica*) (Bråte et al. 2020; Granberg et al. 2020; Teichert et al. 2021).

MP content has been analysed in samples of the suspension feeding bivalve, Greenland smoothcockle (*S. groenlandicus*), and collected in Kongsfjorden and Rijpfjorden, Svalbard. Of the individuals collected, 69% contained one or more MPs with an average of 1.2 ± 1.1 particles per individual (von Friesen 2018). In Arctic rhodolith beds at Northern Svalbard, *H. arctica* was found to contain from 1 to 184 MPs per bivalve (Teichert et al. 2021).

Crustaceans

Preliminary studies have shown that approximately 20% of snow crabs (*Chionoecetes opilio*) in the Barents Sea contained MPs in their stomachs, although chemical polymer identification was not used in this study (Sundet 2014). Snow crabs (whole animals) from the Chukchi Sea contained 0–0.06 MPs per individual and fragments were observed most frequently (Fang et al. 2021). Amphipods (*Gammarus setosus*) collected in the Kongsfjorden–Krossfjorden system, Svalbard, Norway, contained very few anthropogenic microparticles (2 ± 2 per individual) 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 the Rockall through (>2200 m depths) Great Britain contained 1.6 ± 0.4 MPs per g ww (Courtene-Jones et al. 2017). The starfish *Asteria rubens* had highest levels among 11 benthic species from the Chuckchi and Bering Seas (Fang et al. 2018). The mean abundances of MP uptake by the benthos from all sites ranged from 0.02 to 0.46 items per g ww or 0.04–1.67 items per individual (Fang et al. 2018). Starfish (*Ctenodiscus crispatus*) from the Chukchi Sea was reported to contain 0.1–1.4 MPs per individual (Fang et al. 2021).

Recommendations

Sampling

Local conditions should be considered when sampling invertebrates from the field. For example, sampling mussels from suspended ropes/lines in the aquatic environment may result in higher levels of ingested MP derived from the substrate. Therefore, the habitat of any benthic invertebrates must 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 (i.e., when possible, power analyses should be conducted for each species at a given site or area). Directly after collection, invertebrates should be rinsed with seawater to remove debris, with filtered (0.2 μm) milliQ water, and subsequently stored covered in aluminium foil, and lidded in prerinsed glass jars. All samples should be stored frozen (−20 °C) and dark until MP extraction and analysis. Swift handling or freezing after collection prevents sample loss through organisms expelling material from their guts or ingesting plastics in another environment than where they were collected. Open containers or wet filters accommodated on pre-cleaned Petri dishes to control for air dust during sampling should be provided. It is important that all sampling methods are reported, including QA/QC precautions taken in the field (e.g., sampling blanks, recording clothing colour during sample collection; Huntington et al. 2020; Brander et al. 2020; Cowger et al. 2020). Clothing (100% cotton) and (or) clothing with minimal shedding, or easily identifiable fibres should be worn during sample collection and processing.

Recommended metrics that should be reported

To ensure data are comparable across studies, various metrics should be reported. At a minimum, the species, location (including latitude and longitude coordinates), date of sampling (day, month, and year), sampling method, sample size (number of individuals per site/location), depth of collection, size of specimens (average and range), and specimen weight (per individual or pooled) should be included. However, to assess whether data can be compared across studies, and to ensure methods are reproducible for future research, more information should be reported. Further recommendations are presented in the Arctic Monitoring and Assessment Programme (AMAP) monitoring guidelines (AMAP 2021). For sample collection, it is important to provide as much information as possible on the method (e.g., type and size of net used, sampling depth, etc.) to ensure replicability for future spatial or temporal comparisons. Sampling depth is important to report because some species can be distributed across the water column, and the depth of the sample may influence the abundance of MPs in that species. Finally, it is also important to report the sample size of each species and each site, and where possible, ensure that samples sizes are adequate for spatial and temporal comparisons of MP abundance. The minimum sample size will change depending on the species and region, thus statistical power analyses should be conducted when possible. Specimen size, weight (total weight and soft weight), and tissue analysed should be reported, as well as other metrics depending on the species examined (e.g., season, sex, spawning status, moulting stage, and condition index).

For MP collection, extraction, and analysis, it is crucial to report all methods and metrics to assess comparability across studies and to ensure that methods are reproducible for future research. This information should include equipment used, QA/QC procedures followed during each step of the process, detection limits, and measured uncertainty. For extraction methods, both filter type and pore size must be reported, as these directly influence the size of MP particles that can be detected (AMAP 2021).

For the abundance of MPs, it is important to report both total (particles per individual) or relative (particles per gram of wet weight and dry weight) abundance of MPs and the weight of organism, to enable comparison with other studies. It is also important to ensure that abundances (mean, standard deviation, minimum, and maximum) are reported for each species at each site, not just as overall abundances. For example, Gebruk et al. (2021) reported the mean frequency of occurrence of MPs across species, but data for each specific species and site are lacking. Fang et al. (2021) are a great example of how total and relative MP abundance can be presented for each species and site, making it easier to compare to future research. If there are many species and (or) sites, we recommend including this information in supplementary materials.

Finally, in terms of MP characteristics, it is important to report as much information as possible on the MP particles. This should include the colour and particle category for larger particles where this can be determined (fragment, foam, sheet, fibre or other), size (length and width), and mass per tissue weight. These metrics should include mean, standard deviation, and minimum and maximum values for easy comparison. Additionally, polymer type should be reported in a standardized way; thus, we recommend following methods described in Primpke et al. (2017) and Primpke et al. (this issue).

Extraction

Size and weight measurements and preparation for extraction should take place in a clean laminar air flow cabinet to avoid airborne MP contamination. There are several tissue digestion protocols used for invertebrates (reviewed in Lusher et al. 2017, 2020). For example, a gentle and effective digestion protocol based on commercial porcine pancreatic enzymes has been developed specifically using Arctic bivalves (von Friesen et al. 2019). This method will not dissolve chitin, which may be an issue with some invertebrates, e.g., copepods, and a modified approach is recommended for terrestrial isopods (Kallenbach et al. 2021). Potassium hydroxide (KOH) is another option and has been successfully used for bivalves (Gomiero et al. 2019; Bråte et al. 2018, 2020). General recommendation of protocols should await a process of international harmonization, whereby comparability in modifications of methods can be quantified. The most important factor when selecting a digestion method is to control for and keep MP degradation and loss at a minimum, while removing at best the organic matter fraction (i.e., tissue and other particles) to facilitate further MP analysis.

Quality assurance and quality control

In general, systems for quality assurance and quality control (QA/QC) need to be developed. Overall, QA/QC for any invertebrate studies should have sampling blanks and laboratory blanks to account for background contamination throughout collection, extraction, and analysis, especially for microfibres (see review by Brander et al. 2020).

Recommendations for species representing different parts of the ecosystem

Given the lack of harmonized protocols for monitoring in many species and the diversity of species found across the pan-Arctic, the primary recommendation is to focus on suspension feeding species like bivalves, e.g., *M. edulis*, *S. groenlandicus or H. arctica* that can contribute to the monitoring of MPs in the environment, and in future studies, to examine the effects in relation to ecosystems and human health. Field sampling in the Arctic may often result in a collection of other species than expected due to large areas covered and variations in the species distribution. In this case, it is important to keep what is collected for MP analysis and record the species' functional group identity.

As a first level, we recommend long-term monitoring on the widely available suspension feeding bivalves, e.g., *Mytilus* sp. or *S. groenlandicus.* We recognize that size ranges studied are important for uptake and will depend on which methods and instruments are available, although we recommend that the polymer types are chemically identified, for example, by ATR-FTIR for particles >300 µm.

As a second level, we recommend quantifying particles 10–300 µm, and if possible, of lower size, in all invertebrates examined. It is important to develop knowledge to advise on other benthic or pelagic species with different feeding strategies like predator, scavenger, deposit, or suspension feeder. Candidate species to consider include annelids, sea cucumbers (Holothuroidea), Calanus copepods (e.g., *C. glacialis* or *C. finmarchicus*), Gammaridae (e.g., *Gammarus cetosus*), shrimps (*Pandalus* spp.), and krill (Euphausiacea).

As a third level, and for future research, we recommend investigating whether different functional groups of invertebrates have different exposures to MPs, e.g., if there are differences between sessile versus motile species or due to

 Arctic Science **00:** 1–11 (2022) | dx.doi.org/10.1139/AS-2022-0004

different feeding strategies. We need more knowledge on sampling and monitoring strategies regarding pelagic or benthic species, e.g., ice-associated zooplankton, pelagic snails (*Pteropoda* spp.), tunicates, and crabs (e.g., snow crab).

Challenges with regards to filter-feeding organisms

Marine invertebrates, both pelagic and benthic, are constantly filtering a multitude of particles, provoking the development of strategies to reject particles of low nutritional value from actual food items. Many organisms are reported to be selective regarding the uptake of MPs and egest particles as faeces and pseudofaeces, and therefore their suitability as indicator species have been questioned, e.g., by Ward et al. (2019). Such selection processes may affect the bioaccumulation processes and may lead to variation in MP counts between species and among individuals within the same site (Setälä et al. 2016; Gomiero et al. 2019; Piarulli et al. 2019; Bråte et al. 2018, 2020). More knowledge of such selection processes regarding size, shape, and polymer type is needed to evaluate bioindicator species for monitoring.

How to study effects?

Several of the effects observed in laboratory studies with MP exposure are on the sub-organismal level (such as oxidative stress responses, change in gene expression, etc.; Du et al. 2020; Kögel et al. 2020; Vázquez and Rahman 2021).

Histological studies combined with Nile red staining may demonstrate whether MPs are translocated over cell membranes and whether histological changes, e.g., inflammatory responses or lysosomal membrane destabilisation can be observed, e.g., as reported by von Moos et al. (2012).

Transcriptomic technologies such as real-time quantitative PCR (RT-qPCR) and RNA sequencing (RNA-seq) are widely utilized methods in laboratory studies to compare transcriptomic responses (changes in gene expressions) to stressors as, for example, MPs (LeMoine et al. 2018) or change in environmental factors such as ocean acidification (reviewed in Strader et al. 2020). RNA-seq allows for a genome-wide analysis of the transcriptome of the organism and can provide a deeper understanding of the processes and pathways affected by MP exposure. However, such methods are dependent of sequenced genomes, and we still lack such tools for most of the relevant invertebrates in the Arctic.

Data from RNA-seq analysis can either be mapped to a reference genome/transcriptome, or it can be used to assemble a de novo transcriptome which the data are then mapped to (Conesa et al. 2016). While available annotated transcriptomes for zooplankton as a group are still sparse (Lenz et al. 2020), de novo assemblies exist for several species of the Arctic, such as *C. finmarchicus* and *C. glacialis* (Lenz et al. 2014; Bailey et al. 2017). Increasing the number of reference transcriptomes from Arctic organisms can be a useful way forward to address responses to pollutants and other environmental stressors.

By carefully comparing transcriptomic data from animals in laboratory experiments with data obtained from animals in the field, it can be possible to better understand if/how organisms are affected by MP pollution in nature.

Synergy with other Arctic monitoring projects or sampling networks

Knowledge on how food webs in the Arctic may be affected by MP exposure depends on the knowledge on sources, transport, and fate. It is therefore important to collaborate and exchange knowledge on occurrence from the other compartments studied, e.g., sediment, water, fish, birds, and mammals. Strategies and methods for approaching such assessments are presented in the parallel manuscripts in this special issue, specifically water and sediments (Martin et al. this issue), fish (Kögel et al. this issue), birds, and mammals (Lusher et al. this issue).

Many communities in the Arctic harvest bivalves regularly (e.g., mussels and clams). Community-based monitoring sampling programs should be developed to collect bivalves of interest for monitoring levels of ingested MPs. This would also provide samples for effects from plastic contaminants for future studies.

Existing monitoring programs on biological resources and pollutants are already in place for some regions including sampling of sediments and biota making it easy to include sampling for analyses of MPs. The joint Norwegian–Russian ecosystem survey in the Barents Sea performed annually in August to October includes sampling of several fish species, shrimp, and sediments for contaminant monitoring. Floating debris and macrolitter as bycatch in trawls are recorded. MPs are collected from manta trawls from some of the stations (van der Meeren and Prozorkevich 2021). The Norwegian Environmental Agency has recently initiated a monitoring program in Norway for measuring MPs in coastal areas, rivers, and lakes making use of already established sampling from other national monitoring programs to use such resources in an optimal way.

Conclusion

In this paper, we have reviewed studies on MPs in invertebrates in the Arctic and made suggestions on sampling protocols and indicator species. We have primarily recommended that suspension feeding bivalves as indicator species in the Arctic since mussels are widely used and recommended as an indicator species for MP monitoring in coastal regions further south. Although we recognise the challenge with particle selection and egestion in mussels, uptake levels seem to represent recent exposures, although we need more research to understand these selection processes and how they affect the bioaccumulation processes.

We also recommend including species with other feeding strategies like predators, scavengers, and deposit feeders. Future research should include studies on whether different functional groups of invertebrates have different exposures to MPs, e.g., if there are differences between sessile versus motile species or due to different feeding strategies. We need more knowledge on sampling and monitoring strategies regarding pelagic or benthic species, e.g., ice-associated zooplankton, pelagic snails, tunicates, and crabs.

Acknowledgements

This work has been supported by the Fram Centre funded project BARRICADE, the IMR project Plastic and MPs (project no. 15761), and Swedish Environmental Protection Agency (SEPA). This work contributes to a project that has received funding from European Union's Horizon 2020 Coordination and Support Action programme under Grant Agreement 101003805 (EUROqCHARM).

Article information

History dates

Received: 17 January 2022
Accepted: 7 March 2022
Accepted manuscript online: 4 July 2022
Version of record online: 29 November 2022

Notes

This paper is part of a Collection entitled "Litter and Microplastics in the Arctic".

Copyright

Author information

Author ORCIDs

Bjørn Einar Grøsvik https://orcid.org/0000-0003-0794-2212
Amy L. Lusher https://orcid.org/0000-0003-0539-2974

Author contributions

B.E.G.: Conceptualization, Writing – review & editing. M.E.G.: Conceptualization, Writing – review & editing. T.K.: Conceptualization, Writing – review & editing. A.L.L.: Conceptualization, Writing – review & editing. A.G.: Conceptualization, Writing – review & editing. H.P.H.: Conceptualization, Writing – review & editing. A.K.M.: Conceptualization, Writing – review & editing. J.E.B.: Conceptualization, Writing – review & editing. H.D.G.: Conceptualization, Writing – review & editing. K.M.: Conceptualization, Writing – review & editing.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/as-2022-0004.

References

Acuña, J.L., Deibel, D., Saunders, P.A., Booth, B., Hatfield, E. Klein, B., et al. 2002. Phytoplankton ingestion by appendicularians in the North Water. Deep Sea Research Part II: Topical Studies in Oceanography, **49**: 5101–5115. doi:10.1016/S0967-0645(02)00180-7.

Alldredge, A.L. 1981. The impact of appendicularian grazing on natural food concentrations in situ. Limnology and Oceanography, **26**: 247–257. doi:10.4319/lo.1981.26.2.0247.

Amin, R.M., Sohaimi, E.S., Anuar, S.T., and Bachok, Z. 2020. Microplastic ingestion by zooplankton in Terengganu coastal waters, Southern South China Sea. Marine Pollution Bulletin, **150**: 110616. doi:10.1016/j.marpolbul.2019.110616. PMID: 31707243.

AMAP. 2021. AMAP Litter and Microplastics Monitoring Guidelines. Version 1.0. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 257pp. https://www.amap.no/documents/download/6761/inline. [assessed October 2021].

Bailey, A., De Wit, P., Thor, P., Browman, H.I., Bjelland, R. Shema., S., et al. 2017. Regulation of gene expression is associated with tolerance of the Arctic copepod *Calanus glacialis* to CO_2-acidified sea water. Ecology and Evolution, **7**: 7145–7160. doi:10.1002/ece3.3063. PMID: 28944006.

Bedo, A.W., Acuña, J.L., Robins, D., and Harris, R.P. 1993. Grazing in the micron and the sub-micron particle size range: the case of *Oikopleura dioica* (Appendicularia). Bulletin of Marine Science, **53**: 2–14.

Berge, J., Gabrielsen, T.M., Moline, M., and Renaud, P.E. 2012. Evolution of the Arctic Calanus complex: an Arctic marine avocado? Journal of Plankton Research, **34**: 191–195. doi:10.1093/plankt/fbr103. PMID: 22312184.

Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., and Gerdts, G. 2019. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Science Advances, **5**(8): eaax1157. doi:10.1126/sciadv.aax1157. PMID: 31453336.

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., and Gerdts, G. 2017. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. Environmental Science and Technology, **51**(19): 11000–11010. doi:10.1021/acs.est.7b03331. PMID: 28816440.

Botterell, Z.L.R., Beaumont, N., Dorrington, T., Steinke, M., Thompson, R.C., and Lindeque, P.K. 2019. Bioavailability and effects of microplastics on marine zooplankton: a review. Environmental Pollution, **245**: 98–110. doi:10.1016/j.envpol.2018.10.065. PMID: 30415037.

Brander, S.M., Renick, V.C., Foley, M.M., Steele, C., Woo, M. Lusher, A., et al. 2020. Sampling and quality assurance and quality control: a guide for scientists investigating the occurrence of microplastics across matrices. Applied Spectroscopy, **74**(9): 1099–1125. doi:10.1177/0003702820945713. PMID: 32643389.

Bråte, I.L.N., Hurley, R., Iversen, K., Beyer, J., Thomas, K.V. Steindal, C.C., et al. 2018. *Mytilus* spp. as sentinels for monitoring microplastics pollution in Norwegian coastal waters: a qualitative and quantitative study. Environmental Pollution, **243**: 383–393. doi:10.1016/j.envpol.2018.08.077. PMID: 30212794.

Bråte, I.L.N., Hurley, R., Lusher, A., Buenaventura, N., Hultman, M., Halsband, C., and Green, N. 2020. Microplastics in marine bivalves from the Nordic environment. Nordisk Ministerråd, Copenhagen, Denmark. doi:10.6027/temanord2020-504.

Buhl-Mortensen, L., and Buhl-Mortensen, P. 2017. Marine litter in the Nordic Seas: distribution composition and abundance. Marine Pollution Bulletin, **125**: 260–270. doi:10.1016/j.marpolbul.2017.08.048. PMID: 28844455.

Choe, N., and Deibel, D. 2008. Temporal and vertical distributions of three appendicularian species (Tunicata) in Conception Bay, Newfoundland. Journal of Plankton Research, **30**: 969–979. doi:10.1093/plankt/fbn064.

Choy, C.A., Robison, B.H., Gagne, T.O., Erwin, B., Firl, E. Halden, R.U., et al. 2019. The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. Scientific Reports, **9**: 7843. doi:10.1038/s41598-019-44117-2.

Collard, F., and Ask, A. 2021. Plastic ingestion by Arctic fauna: a review. Science of the Total Environment, **786**: 147462. doi:10.1016/j.scitotenv.2021.147462.

Cole, M., Coppock, R., Lindeque, P.K., Altin, D., Reed, S. Pond, D.W., et al. 2019. Effects of nylon microplastic on feeding, lipid accumulation, and moulting in a coldwater copepod. Environmental Science & Technology, **53**: 7075–7082. doi:10.1021/acs.est.9b01853.

Cole, M., Lindeque, P.K., Fileman, E., Clark, J., Lewis, C., Halsband, C., and Galloway, T.S., 2016. Microplastics alter the properties and sinking rates of zooplankton faecal pellets. Environmental Science and Technology, **50**: 3239–3246. doi:10.1021/acs.est.5b05905. PMID: 26905979.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., and Galloway, T.S. 2015. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environmental Science and Technology, **49**(2): 1130–1137. doi:10.1021/es504525u. PMID: 25563688.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., and Galloway, T.S. 2013. Microplastics ingestion by zooplankton. Environmental Science and Technology, **47**(12): 6646–6655. doi:10.1021/es400663f. PMID: 23692270.

Conesa, A., Madrigal, P., Tarazona, S., Gomez-Cabrero, D., Cervera, A. Mcpherson, A., et al. 2016. A survey of best practices for RNA-seq data analysis. Genome Biology, **17**: 13. doi:10.1186/s13059-016-0881-8. PMID: 26813401.

Conley, K.R., and Sutherland, K.R. 2017. Particle shape impacts export and fate in the ocean through interactions with the globally abundant appendicularian *Oikopleura dioica*. PLOS ONE, **12**: e0183105. doi:10.1371/journal.pone.0183105. PMID: 28854260.

Coppock, R.L., Galloway, T.S., Cole, M., Fileman, E.S., Queirós, A.M., and Lindeque, P.K. 2019. Microplastics alter feeding selectivity and faecal density in the copepod, *Calanus helgolandicus*. Science of The Total Environment, **687**: 780–789. doi:10.1016/j.scitotenv.2019.06.009. PMID: 31412481.

Cowger, W., Gray, A., Christiansen, S.H., DeFrond, H., Deshpande, A.D. Hemabessiere, L., et al. 2020. Critical review of processing and classification techniques for images and spectra in microplastic research. Appl. Spectrosc. **74**: 989–1010. doi:10.1177/0003702820929064. PMID: 32500727.

Courtene-Jones, W., Quinn, B., Gary, S.F., Mogg, A.O.M., and Narayanaswamy, B.E. 2017. Microplastic pollution identified in deep-sea water and ingested by benthic invertebrates in the Rockall Trough, North Atlantic Ocean. Environmental Pollution, **231**: 271–280. doi:10.1016/j.envpol.2017.08.026.

Dehaut, A., Hermabessiere, L., and Duflos, G. 2019. Current frontiers and recommendations for the study of microplastics in seafood. TrAC Trends in Analytical Chemistry, **116**: 346–359. doi:10.1016/j.trac.2018.11.011.

Deibel, D. 1988. Filter feeding by *Oikopleura vanhoeffeni*: grazing impact on suspended particles in cold ocean waters. Marine Biology, **99**: 177–186. doi:10.1007/BF00391979.

Deibel, D., and Lee, S.H. 1992. Retention efficiency of sub-micrometer particles by the pharyngeal filter of the pelagic tunicate *Oikopleura vanhoeffeni*. Marine Ecology Progress Series, **81**: 25–30. doi:10.3354/meps081025.

Deibel, D., Saunders, P.A., and Stevens, C.J. 2017. Seasonal phenology of appendicularian tunicates in the North Water, Northern Baffin Bay. Polar Biology, **40**: 1289–1310. https://link.springer.com/article/10.1007%2Fs00300-016-2053-4. [assessed October 2021]. doi:10.1007/s00300-016-2053-4.

Desforges, J.-P.W., Galbraith, M., and Ross, P.S. 2015. Ingestion of microplastics by zooplankton in the Northeast Pacific Ocean. Archives of Environmental Contamination and Toxicology, **69**: 320–330. doi:10.1007/s00244-015-0172-5. PMID: 26066061.

Dong, H., Wang, L., Wang, X., Xu, L., Chen, M., Gong, P., and Wang, C. 2021. Microplastics in a remote lake basin of the Tibetan Plateau: impacts of atmospheric transport and glacial melting. Environmental Science and Technology, **55**(19): 12951–12960. doi:10.1021/acs.est.1c03227. PMID: 34524792.

Du, J., Xu, S., Zhou, Q., Li, H., Fu, L., and Tang, J., et al. 2020. A review of microplastics in the aquatic environmental: distribution, transport, ecotoxicology, and toxicological mechanisms. Environmental Science and Pollution Research, **27**(11): 11494–11505. doi:10.1007/s11356-020-08104-9. PMID: 32088821.

Erni-Cassola, G., Zadjelovic, V., Gibson, M.I., and Christie-Oleza, J.A. 2019. Distribution of plastic polymer types in the marine environment: a meta-analysis. Journal of Hazardous Materials, **369**: 691–698. doi:10.1016/j.jhazmat.2019.02.067. PMID: 30826562.

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., and Stohl, A. 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nat Commun, **11**(1): 3381. doi:10.1038/s41467-020-17201-9. PMID: 32665541.

Fang, C., Zheng, R., Hong, F., Jiang, Y., Chen, J. Lin, H., et al. 2021. Microplastics in three typical benthic species from the Arctic: occurrence, characteristics, sources, and environmental implications. Environmental Research, **192**: 110326. doi:10.1016/j.envres.2020.110326. PMID: 33068580.

Fang, C., Zheng, R., Zhang, Y., Hong, F., Mu, J. Chen, M., et al. 2018. Microplastics contamination in benthic organisms from the Arctic and sub-Arctic regions. Chemosphere, **209**: 298–306. doi:10.1016/j.chemosphere.2018.06.101. PMID: 29933166.

Fenaux, R., Bone, Q., and Deibel, D. 1998. Appendicularian distribution and zoogeography. *In* The biology of pelagic tunicates. *Edited by* Q. Bones. Oxford University Press, Oxford.

Fernández, D., López-Urrutia, Á., Fernández, A., Acuña, J.L., and Harris, R. 2004. Retention efficiency of 0.2 to 6 μm particles by the appendicularians *Oikopleura dioica* and *Fritillaria borealis*. Marine Ecology Progress Series, **266**: 89–101. doi:10.3354/meps266089.

Galloway, T.S., Cole, M., and Lewis, C. 2017. Interactions of MP debris throughout the marine ecosystem. Nature Ecology and Evolution, **1**: 116. doi:10.1038/s41559-017-0116. PMID: 28812686.

Gebruk, A., Zalota, A.K., Dgebuadze, P., Ermilova, Y., Spiridonov, V.A. Shabalin, N., et al. 2021. Trophic niches of benthic crustaceans in the Pechora Sea suggest that the invasive snow crab *Chionoecetes opilio* could be an important competitor. Polar Biology, **44**: 57–71. doi:10.1007/s00300-020-02775-3.

Gomiero, A., Strafella, P., Øysæd, K.B., and Fabi, G. 2019. First occurrence and composition assessment of microplastics in native mussels collected from coastal and offshore areas of the Northern and Central Adriatic Sea. Environmental Science and Pollution Research, **26**(24): 24407–24416. doi:10.1007/s11356-019-05693-y. PMID: 31230239.

Granberg, M.E., von Friesen, L.W., Ask, A., Collard, F., Magnusson, K. Eriksson Wiklund, A.-K., et al. 2020. Microlitter in Arctic marine benthic food chains and potential effects on sediment dwelling fauna. TemaNord, 528. Nordic Council of Ministers, Copenhagen, Denmark. doi:10.6027/temanord2020-528.

Grøsvik, B.E., Prokhorova, T., Eriksen, E., Krivosheya, P., Horneland, P.A., and Prozorkevich, D. 2018. Assessment of marine litter in the Barents Sea, a part of the joint Norwegian–Russian ecosystem survey. Frontiers in Marine Science, **5**: 72. doi:10.3389/fmars.2018.00072.

Group of Experts on Scientific Aspects of Marine Environmental Protection (GESAMP). 2019. Guidelines for the Monitoring and Assessment of Plastic Litter and Microplastics in the Ocean. GESAMP, London, UK. pp. 130. Available from http://www.gesamp.org/publications/guidelines-for-the-monitoring-and-assessment-of-plastic-litter-in-the-ocean. [assessed October 2021].

Halldórsson, H.P., and Guls, H.D. 2018. Könnun á örplastmengun í kræklingi (*Mytilus edulis*) við Ísland [Microplastics in blue mussels (*Mytilus edulis*) in Iceland 2018]. Report for the Environment Agency of Iceland, Reykjavík, Iceland. Available from https://www.ust.is/library/sida/haf-og-vatn/Orplast_kraeklingur_2018_skyrsla_UST_HI_Sudurnes_Leidrett_2019.pdf. [assessed October 2021].

Hop, H., Wold, A., Vihtakari, M., Daase, M., Kwasniewski, S. Gluchowska, M., et al. 2019. Zooplankton in Kongsfjorden (1996–2016) in relation to climate change. *In* The ecosystem of Kongsfjorden, Svalbard. Advances in Polar Ecology, vol. **2**. *Edited by* H. Hop and C. Wiencke. Springer International Publishing, Cham. doi:10.1007/978-3-319-46425-1_7.

Huntington, A., Corcoran, P.L., Jantunen, L., Thaysen, C., Bernstein, S., Stern, G.A., and Rochman, C.M. 2020. A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding Eastern Canadian Arctic waters of Nunavut. FACETS, **5**: 432–454. doi:10.1139/facets-2019-0042.

Huserbråten, M.B.O., Hattermann, T., Broms, C., and Albretsen, J. 2022. Trans-polar drift-pathways of riverine European microplastic. Scientific Reports, **12**(1): 3016. doi:10.1038/s41598-022-07080-z. PMID: 35301340.

Kaiser, D., Kowalski, N., and Waniek, J.J. 2017. Effects of biofouling on the sinking behavior of microplastics. Environmental Research Letters, **12**: 124003. doi:10.1088/1748-9326/aa8e8b.

Kallenbach, E.M.F., Hurley, R.R., Lusher, A., and Friberg, N. 2021. Chitinase digestion for the analysis of microplastics in chitinaceous organisms using the terrestrial isopod *Oniscus asellus*. L. as a model organism. Science of The Total Environment, **786**: 147455. doi:10.1016/j.scitotenv.2021.147455. PMID: 33964777.

Katija, K., Choy, C.A., Sherlock, R.E., Sherman, A.D., and Robison, B.H. 2017. From the surface to the seafloor: how giant larvaceans transport microplastics into the deep sea. Science Advances, **3**: e1700715. doi:10.1126/sciadv.1700715. PMID: 28835922.

Koelmans, A.A. 2015. Modeling the role of microplastics in bioaccumulation of organic chemicals to marine aquatic organisms. A critical review. *In* Marine anthropogenic litter. *Edited by* M. Bergmann, L. Gutow and M. Klages. Springer, Cham. doi:10.1007/978-3-319-16510-3_11.

Kögel, T., Bjorøy, Ø., Toto, B., Bienfait, A.M., and Sanden, M. 2020. Micro- and nanoplastic toxicity on aquatic life: determining factors. Science of The Total Environment, **709**: 136050. doi:10.1016/j.scitotenv.2019.136050. PMID: 31887526.

Kowalski, N., Reichardt, A.M., and Waniek, J.J. 2016. Sinking rates of microplastics and potential implications of their alteration by physical, biological, and chemical factors. Marine Pollution Bulletin, **109**: 310–319. doi:10.1016/j.marpolbul.2016.05.064. PMID: 27297594.

Kvale, K.F., Friederike Prowe, A.E., and Oschlies, A. 2020. A critical examination of the role of marine snow and zooplankton fecal pellets in removing ocean surface microplastic. Frontiers in Marine Science, **6**: 808. doi:10.3389/fmars.2019.00808.

Lehtiniemi, M., Hartikainen, S., Näkki, P., Engström-Öst, J., Koistinen, A., and Setälä, O. 2018. Size matters more than shape: ingestion of primary and secondary microplastics by small predators. Food Webs, **17**: e00097. doi:10.1016/j.fooweb.2018.e00097.

Lemoine, C.M.R., Kelleher, B.M., Lagarde, R., Northam, C., Elebute, O.O., and Cassone, B.J. 2018. Transcriptional effects of polyethylene microplastics ingestion in developing zebrafish (*Danio rerio*). Environmental Pollution, **243**: 591–600. doi:10.1016/j.envpol.2018.08.084. PMID: 30218869.

Lenz, P.H., Lieberman, B., Cieslak, M.C., Roncalli, V., and Hartline, D.K. 2020. Transcriptomics and metatranscriptomics in zooplankton: wave of the future? Journal of Plankton Research, **43**: 3–9. doi:10.1093/plankt/fbaa058.

Lenz, P.H., Roncalli, V., Hassett, R.P., Wu, L.-S., Cieslak, M.C., Hartline, D.K., and Christie, A.E. 2014. De novo assembly of a transcriptome for *Calanus finmarchicus* (Crustacea, copepoda)— the dominant zooplankter of the North Atlantic Ocean. PLOS ONE, **9**: e88589. doi:10.1371/journal.pone.0088589. PMID: 24586345.

Li, J., Lusher, A.L., Rotchell, J.M., Deudero, S., Turra, A. Bråte, I.N.N., et al. 2019. Using mussel as a global bioindicator of coastal microplastic pollution. Environmental Pollution, **244**: 522e533. doi:10.1016/j.envpol.2018.10.032.

Lohmann, R. 2017. Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans—but should microplastics be considered POPs themselves? Integrated Environmental Assessment and Management, **13**(3): 460–465. doi:10.1002/ieam.1914. PMID: 28440937.

Long, M., Moriceau, B., Gallinari, M., Lambert, C., Huvet, A., Raffray, J., and Soudant, P. 2015. Interactions between microplastics and phytoplankton aggregates: impact on their respective fates. Marine Chemistry, **175**: 39–46. doi:10.1016/j.marchem.2015.04.003.

Lusher, A.L., Munno, K., Hermabessiere, L., and Carr, S. 2020. Isolation and extraction of microplastics from environmental samples: an evaluation of practical approaches and recommendations for further harmonization. Applied Spectroscopy, **74**(9): 1049–1065. doi:10.1177/0003702820938993. PMID: 32893667.

Lusher, A.L., Tirelli, V., O'Connor, I., and Officer, R. 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Scientific Reports, **5**(1): 14947. doi:10.1038/srep14947. PMID: 26446348.

Lusher, A.L., Welden, N.A., Sobral, P., and Cole, M. 2017. Sampling, isolating and identifying microplastics ingested by fish and invertebrates. Analytical Methods, **9**(9): 1346–1360. https://pubs.rsc.org/en/content/articlelanding/2017/ay/c6ay02415. [assessed October 2021]. doi:10.1039/C6AY02415G.

Möhlenkamp, P., Purser, A., and Thomsen, L. 2018. Plastic microbeads from cosmetic products: an experimental study of their hydrodynamic behaviour, vertical transport and resuspension in phytoplankton and sediment aggregates. Elementa: Science of the Anthropocene, **6**: 61. doi:10.1525/elementa.317.

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., and Thompson, R.C. 2014. Global warming releases microplastics legacy frozen in Arctic Sea ice. Earth's Future, **2**: 315–320. doi:10.1002/2014ef000240.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C. Krumpen, T., et al. 2018. Arctic sea ice is an important temporal sink and means of transport for microplastics. Nature Communications, **9**: 1505. doi:10.1038/s41467-018-03825-5. PMID: 29692405.

Phuong, N.N., Zalouk-Vergnoux, A., Poirier, L., Kamari, A., Châtel, A., Mouneyrac, C., and Lagarde, F. 2016. Is there any consistency between the microplastics found in the field and those used in laboratory experiments? Environmental Pollution, **211**: 111–123. doi:10.1016/j.envpol.2015.12.035. PMID: 26745396.

Piarulli, S., Scapinello, S., Comandini, P., Magnusson, K., Granberg, M. Wong, J.X.W., et al. 2019. Microplastics in wild populations of the omnivorous crab *Carcinus aestuarii*: a review and a regional-scale test of extraction methods, including microfibres. Environmental Pollution, **251**: 117–127. doi:10.1016/j.envpol.2019.04.092. PMID: 31075692.

Porter, A., Lyons, B.P., Galloway, T.S., and Lewis, C. 2018. Role of marine snows in microplastic fate and bioavailability. Environmental Science and Technology, **52**(12): 7111–7119. doi:10.1021/acs.est.8b01000. PMID: 29782157.

Primpke, S., Lorenz, C., Rascher-Friesenhausen, R., and Gerdts, G. 2017. An automated approach for microplastics analysis using focal plane array (FPA) FTIR microscopy and image analysis. Analytical Methods, **9**: 1499. doi:10.1039/c6ay02476a.

Rochman, C.M., Lewison, R.L., Eriksen, M., Allen, H., Cook, A.-M., and Teh, S.J. 2014. Polybrominated diphenyl ethers (PBDEs) in fish tissue may be an indicator of plastic contamination in marine habitats. Science of The Total Environment, **476**: 622–633. doi:10.1016/j.scitotenv.2014.01.058. PMID: 24496035.

Rodríguez-Torres, R., Almeda, R., Kristiansen, M., Rist, S., Winding, M.S., and Nielsen, T.G. 2020. Ingestion and impact of microplastics on Arctic Calanus copepods. Aquatic Toxicology, **228**: 105631. doi:10.1016/j.aquatox.2020.105631. PMID: 32992089.

Rummel, C.D., Jahnke, A., Gorokhova, E., Kuhnel, D., and Schmitt-Jansen, M. 2017. Impacts of biofilm formation on the fate and potential effects of microplastics in the aquatic environment. Environmental Science and Technology Letters, **4**: 258–267. doi:10.1021/acs.estlett.7b00164.

Setälä, O., Fleming-Lehtinen, V., and Lehtiniemi, M. 2014. Ingestion and transfer of microplastics in the planktonic food web. Environmental Pollution, **185**: 77–83. doi:10.1016/j.envpol.2013.10.013. PMID: 24220023.

Setälä, O., Norkko, J., and Lehtiniemi, M. 2016. Feeding type affects microplastics ingestion in a coastal invertebrate community. Marine Pollution Bulletin, **102**: 95–101. doi:10.1016/j.marpolbul.2015.11.053. PMID: 26700887.

Strader, M.E., Wong, J.M., and Hofmann, G.E. 2020. Ocean acidification promotes broad transcriptomic responses in marine metazoans: a literature survey. Frontiers in Zoology, **17**: 7. doi:10.1186/s12983-020-0350-9. PMID: 32095155.

Sun, X., Li, Q., Zhu, M., Liang, J., Zheng, S., and Zhao, Y. 2017. Ingestion of microplastics by natural zooplankton groups in the Northern South China Sea. Marine Pollution Bulletin, **115**: 217–224. doi:10.1016/j.marpolbul.2016.12.004. PMID: 27964856.

Sun, X., Liang, J., Zhu, M., Zhao, Y., and Zhang, B. 2018a. Microplastics in seawater and zooplankton from the Yellow Sea. Environmental Pollution, **242**: 585–595. doi:10.1016/j.envpol.2018.07.014.

Sun, X., Liu, T., Zhu, M., Liang, J., Zhao, Y., and Zhang, B. 2018b. Retention and characteristics of microplastics in natural zooplankton taxa from the East China Sea. Science of The Total Environment, **640-641**: 232–242. doi:10.1016/j.scitotenv.2018.05.308.

Sundet, J. 2014. Status on the snow crab in the Barents Sea (No. Joint Russian–Norwegian report series, no. 18/2014), Presentation on the Norwegian–Russian workshop on king and snow crabs in the Barents Sea, Tromsø, 11–12 March 2014. Available from https://www.hi.no/resources/publikasjoner/rapport-fra-havforskningen/2014/hi-rapp_18-2014_king_and_snow_til_web.pdf. [assessed October 2021].

Teichert, S., Löder, M.G.J., Pyko, I., Mordek, M., Schulbert, C., Wisshak, M., and Laforsch, C. 2021. Microplastic contamination of the drilling bivalve *Hiatella arctica* in Arctic Rhodolith beds. Scientific Reports, **11**: 14574. doi:10.1038/s41598-021-93668-w.

Tekman, M.B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., and Bergmann, M. 2020. Tying up loose ends of microplastics pollution in the Arctic: distribution from the sea surface through the water column to deep-sea sediments at the HAUSGARTEN observatory. Environmental Science and Technology, **54**: 4079–4090. doi:10.1021/acs.est.9b06981. PMID: 32142614.

Trevail, A.M., Gabrielsen, G.W., Kühn, S., and Van Franeker, J.A. 2015. Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (*Fulmarus glacialis*). Polar Biol. **38**: 975–981. doi:10.1007/s00300-015-1657-4.

Turner, J.T. 2015. Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump. Progress in Oceanography, **130**: 205–248. doi:10.1016/j.pocean.2014.08.005.

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

Vargas, C.A., and González, H.E. 2004. Plankton community structure and carbon cycling in a coastal upwelling system. I. Bacteria, microprotozoans and phytoplankton in the diet of copepods and appendicularians. Aquatic Microbial Ecology, **34**: 151–164. doi:10.3354/ame034151.

Vázquez, O.A., and Rahman, S. 2021. An ecotoxicological approach to microplastics on terrestrial and aquatic organisms: a systematic review in assessment, monitoring and biological impact. Environmental Toxicology and Pharmacology, **84**: 103615. doi:10.1016/j.etap.2021.103615. PMID: 33607259.

Villarrubia-Gómez, P., Cornell, S.E., and Fabres, J. 2018. Marine plastic pollution as a planetary boundary threat—the drifting piece in the sustainability puzzle. Marine Policy, **96**: 213–220. doi:10.1016/j.marpol.2017.11.035.

von Friesen, L.W. 2018. Anthropogenic microlitter in Svalbard Waters—development of novel extraction methods, determination of distribution and investigationof potential sources. University of Gothenburg, Gothenburg, Sweden.

von Friesen, L.W., Granberg, M.E., Hassellöv, M., Gabrielsen, G.W., and Magnusson, K. 2019. An efficient and gentle enzymatic digestion protocol for the extraction of microplastics from bivalve tissue. Marine Pollution Bulletin, **142**: 129–134. doi:10.1016/j.marpolbul.2019.03.016. PMID: 31232285.

von Friesen, L.W., Granberg, M.E., Pavlova, O., Magnusson, K., Hassellöv, M., and Gabrielsen, G.W. 2020. Sea ice and a wastewater outlet identified as hotspots for anthropogenic microlitter in Svalbard waters. Environment International, **139**: 105511. doi:10.1016/j.envint.2020.105511. PMID: 32278193.

von Moos, N., Burkhardt-Holm, P., and Köhler, A. 2012. Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. Environmental Science and Technology, **46**(20): 11327–11335. doi:10.1021/es302332w. PMID: 22963286.

Vroom, R.J.E., Koelmans, A.A., Besseling, E., and Halsband, C. 2017. Aging of microplastics promotes their ingestion by marine zooplankton. Environmental Pollution, **231**: 987–996. doi:10.1016/j.envpol.2017.08.088. PMID: 28898955.

Ward, J.E., Zhao, S., Holohan, B.A., Mladinich, K.M., Griffin, T.W., Wozniak, J., and Shumway, S.E. 2019. Selective ingestion and egestion of plastic particles by the blue mussel (*Mytilus edulis*) and eastern oyster (*Crassostrea virginica*): implications for using bivalves as bioindicators of microplastic pollution. Environmental Science and Technology, **53**: 8776–8784. doi:10.1021/acs.est.9b02073. PMID: 31305074.

Wieczorek, A.M., Croot, P.L., Lombard, F., Sheahan, J.N., and Doyle, T.K. 2019. Microplastic ingestion by gelatinous zooplankton may lower efficiency of the biological pump. Environmental Science and Technology, **53**: 5387–5395. doi:10.1021/acs.est.8b07174.

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.J., Coppock, R. Sleight, V., et al. 2014. The deep sea is a major sink for MP debris. Royal Society Open Science, **1**(4): 143017. doi:10.1098/rsos.140317.

Woods, M.N., Stack, M.E., Fields, D.M., Shaw, S.D., and Matrai, P.A. 2018. Microplastic fiber uptake, ingestion, and egestion rates in the blue mussel (*Mytilus edulis*). Marine Pollution Bulletin, **137**: 638–645. doi:10.1016/j.marpolbul.2018.10.061. PMID: 30503478.

Zhao, S., Ward, J.E., Danley, M., and Mincer, T.J. 2018. Field-based evidence for microplastics in marine aggregates and mussels: implications for trophic transfer. Environmental Science and Technology, **52**(19): 11038–11048. doi:10.1021/acs.est.8b03467. PMID: 30156835.

Zheng, S., Zhao, Y., Liangwei, W., Liang, J., Liu, T. Zhu, M., et al. 2020. Characteristics of microplastics ingested by zooplankton from the Bohai Sea, China. Science of The Total Environment, **713**: 136357. doi:10.1016/j.scitotenv.2019.136357.