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Status and future recommendations for recording and monitoring litter on the Arctic seafloor

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Abstract

Marine litter in the Arctic Basin is influenced by transport from Atlantic and Pacific waters. This highlights the need for harmonization of guidelines across regions. Monitoring can be used to assess temporal and spatial trends but can also be used to assess if environmental objectives are reached, for example, to evaluate the effectiveness of mitigation measures. Seafloor monitoring by trawling needs substantial resources and specific sampling strategies to be sufficiently robust to demonstrate changes over time. Observation and visual evaluation in shallow and deep waters using towed camera systems, remotely operated underwater vehicles, and submersibles are well suited for the Arctic environment. The use of imagery still needs to be adjusted through automation and image analyses, including deep learning approaches and data management, but will also serve to monitor areas with a rocky seafloor. We recommend developing a monitoring plan for seafloor litter by selecting representative sites for visual inspection that cover different depths and substrata in marine landscapes, and recording the litter collected or observed across all forms of seafloor sampling or imaging. We need better coverage and knowledge of status of seafloor litter for the whole Arctic and recommend initiatives to be taken for regions where such knowledge is lacking.

Key words: circumpolar, plastic pollution, sea bed, standardization, harmonization

1 Introduction

The seafloor accounts for 70% of the Earth's surface and is an important carbon sink. It has also been argued that the seafloor acts as a final sink for marine litter, including microplastics (<5 mm) (Woodall et al. 2014; Tekman et al. 2020). Marine litter is defined as any persistent, manufactured, or processed solid material discarded, disposed of, or abandoned in the marine environment (UNEP 2009). This article concerns macrolitter, items larger than 2 cm on the seafloor, which accounts for over 70%–74% of all marine litter by mass (UNEP 2005; Madricardo et al. 2020; https://litterbase.awi.de, status March 2022). Benthic microlitter (<5 mm) is covered by Martin et al. (2022). Plastic accounts for 66% of the litter recorded on the seafloor (https://litterbase.awi.de, status March 2022), resulting from mismanagement of plastic waste or deliberate disposal. This high proportion does not come as a surprise given that 50% of the plastic present in municipal waste has a density higher than seawater and sinks directly to the seafloor (Engler 2012). Over time, though, even lighter plastic descends due to physical and biological processes, i.e., biofouling and ballasting processes (Porter et al. 2018) and hydrographic processes including mixing and deep-water cascading (van Sebille et al. 2020). Despite the importance of the seafloor as a sink for marine litter, it remains one of the least explored habitats on Earth due to technical challenges, especially in the Arctic where financial and logistical constraints come on top (Mallory et al. 2018). Consequently, the scale and distribution of seafloor pollution are poorly studied and understood, especially in the Arctic region.

Although the deep seafloor has long been pictured as a sparsely inhabited moonscape, research over the past decades has unveiled a high level of biodiversity (e.g., Herring 2002). However, little is known about the effects of plastic debris on these rich communities. It has been suggested that litter items such as plastic bags can smother and damage erect epibenthic organisms, such as cold-water corals and sponges, leading to injury, breakage, mortality, and disease (Yoshikawa and Asoh 2004; Chiappone et al. 2005; Lamb et al. 2018; Mouchi et al. 2019; Ying et al. 2021). Litter on the seafloor can cause anoxia to the underlying sediment, which could alter biogeochemistry and benthic community structure (Green et al. 2015). Simultaneously, it has the potential to serve as a substrate for the attachment of sessile biota in sedimentary environments and to thereby alter community structure and biodiversity (Schulz et al. 2010; Mordecai et al. 2011; Song et al. 2021). Debris from fisheries in particular represents a threat to mobile biota through processes such as ghost fishing, increasing benthic mortality (Matsuoka et al. 2005). Plastic litter is also ingested by benthic organisms and demersal fish. Despite increasing evidence, the actual effects of these interactions on benthic biota and ecosystems are still poorly constrained (Canals et al. 2021).

The objectives of this work are to (i) describe the current status of knowledge of litter on the Arctic seafloor, (ii) provide an overview of methods used for marine litter quantification, and (iii) discuss how to improve the recording and monitoring of litter in the Arctic in the future. This paper builds on the recommendations on seafloor monitoring from AMAP (2021) but is further discussed and developed.

2 Status of global science

The highest density levels for marine litter are typically recorded in coastal areas. For example, a mean litter density of 2510 kg km^{-2} was observed along the Norwegian coast from Ålesund to Lofoten and 227 kg km^{-2} from Lofoten to the Russian border. The differences were caused by lower population densities from Lofoten to the Russian border and some hot spots for fisheries-related litter outside harbours (Buhl-Mortensen and Buhl-Mortensen 2017, 2018). Fisheries-related litter, which dominated in both studies, consists of wires, nets, and ropes. By weight metal (wires) dominated, whereas plastic (nets and ropes) often dominated by volume. This observation concurs with findings from other coastal areas with high fishing and aquaculture activities, such as oceanic ridges and seamounts (Pham et al. 2014; Woodall et al. 2015).

Plastic on the seafloor was first recorded in McMurdo Sound, Antarctica (Dayton and Robilliard 1971) and the Skagerrak in 1972 (Holmström 1975), followed by the Mediterranean (e.g., Galil et al. 1995; Galgani et al. 1995*a*, 1996; Stefatos et al. 1999; Katsanevakis and Katsarou 2004; Strafella et al. 2019), other European coasts (Galgani et al. 1995*a*, 1995*b*, 2000), the United States (June 1990; Moore and Allen 2000; Keller et al. 2010; Morét-Ferguson et al. 2010; Watters et al. 2010; Schlining et al. 2013; Law et al. 2020), and other areas (Lee et al. 2006; Fischer et al. 2015; Shimanaga and Yanagi 2016; Chiba et al. 2018). Litter has also been recorded in the Arctic, including Alaska and the Bering Sea (Jewett 1976; Feder et al. 1978; June 1990; Hess et al. 1999; Tekman et al. 2017), as well as the deep seafloor (Galgani and Lecornu 2004; Pace et al. 2007; Keller et al. 2010; Mordecai et al. 2011; Bergmann and Klages 2012; Wei et al. 2012; Pham et al. 2013; Ramirez-Llodra et al. 2013; Amon et al. 2020), including hadal trenches such as the Mariana Trench, the deepest region on Earth (Peng et al. 2018). Litter densities on the seafloor range between 30 and 20 000 items km^{-2} (Keller et al. 2010; Pham et al. 2014; Buhl-Mortensen and Buhl-Mortensen 2017; Pierdomenico et al. 2019) and are strongly influenced by the distance to the coastline, regional population density, rivers, depth, marine landscapes, sampling and analysis approaches, hydrography, proximity to shipping routes and other anthropogenic activities (Strafella et al. 2015, 2019; Canals et al. 2021).

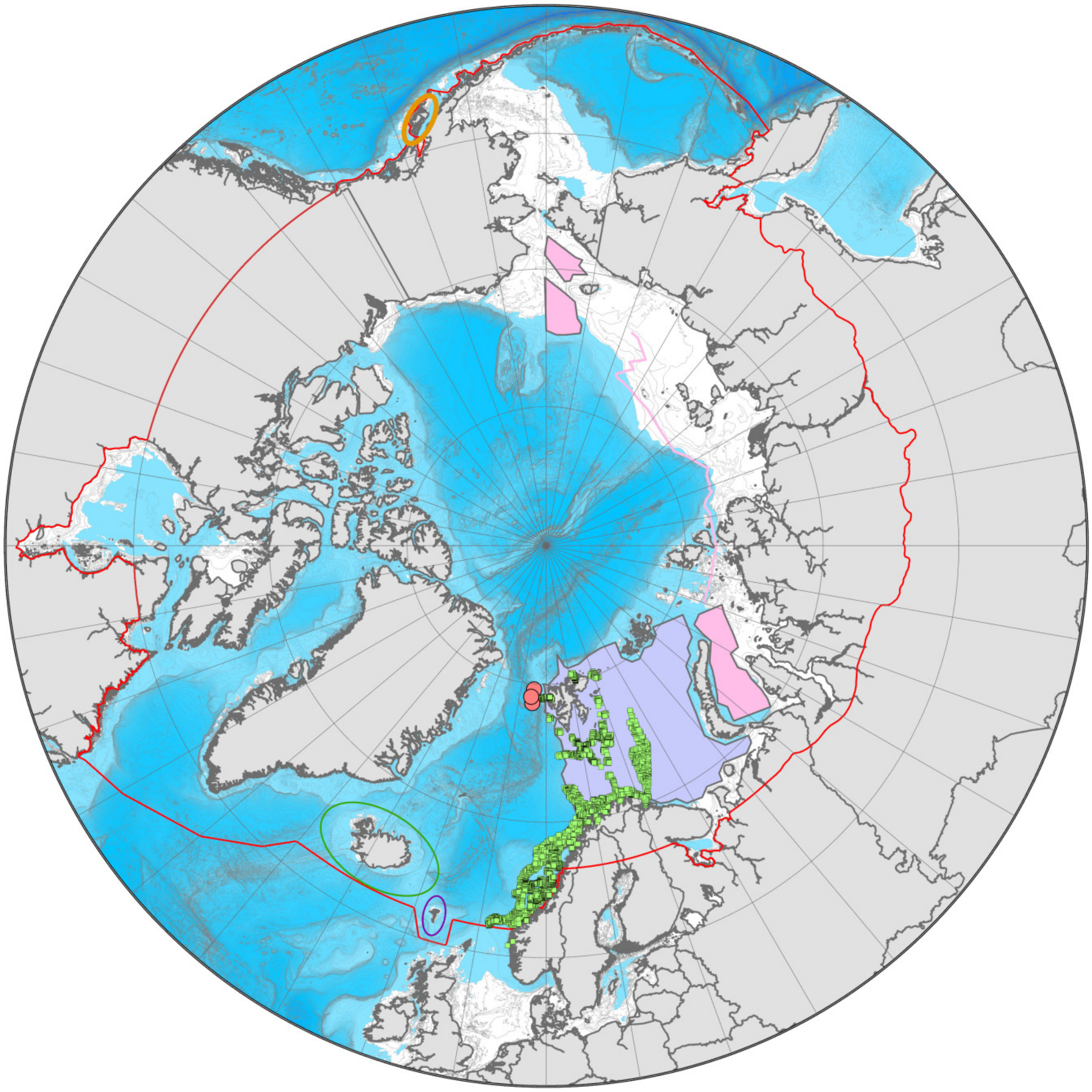
Outside of the coastal regions, the highest marine litter densities have been found in submarine canyons, while continental shelves and ocean ridges typically have the lowest densities (Galgani et al. 2000; Ramirez-Llodra et al. 2011; Pham et al. 2014; Woodall et al. 2015; Buhl-Mortensen and Buhl-Mortensen 2017, 2018). This suggests there are transport mechanisms for seafloor litter to the lowest points in the world's oceans. For example, the densities of litter in the Ryukyu Trench and in the basin of Okinawa in the Northwest Pacific ranged from 8 to 121 kg km^{-2}, whereas values in nearby shallower continental slopes or abyssal plains ranged from 0.03 to 9 kg km^{-2} (Shimanaga and Yanagi 2016). Similarly, the densities of marine litter in the Mediterranean collected by trawling from deep waters (1400–3000 m depth) ranged from 400 kg km^{-2} at the continental slope south of Palma de Mallorca to densities between 70 and 180 kg km^{-2} at sites away from the coast (Galgani et al. 2000; Pham et al. 2014). In the shallower waters of the North-Central Adriatic Sea, densities between 41 $\pm$ 9.6 and 143 $\pm$ 27 kg km^{-2} were observed (Strafella et al. 2015, 2019). In the European part of the Atlantic Ocean, densities of 43–74 kg km^{-2} have been recorded in the Bay of Biscay (Lopez-Lopez et al. 2017). A mean of 123 kg km^{-2} has been estimated for the Norwegian shelf and the slope of the Norwegian Sea, and a mean of 154 kg km^{-2} has been recorded offshore in the Barents Sea (Buhl-Mortensen and Buhl-Mortensen 2017).

3 Seafloor survey efforts of the Arctic seafloor

In sub-Arctic regions, marine litter was first reported as bycatch from trawls conducted in 1975/1976 in the Bering Sea (Jewett 1976; Feder et al. 1978). In June 1990, marine litter from trawls in the same area specifically reported the presence of plastic litter items. The ongoing Norwegian seafloor mapping program Mareano (www.mareaNo.no) started in 2005 and has so far conducted >2000 (~700 m long) video transects with >1200 transects conducted in the Norwegian and the Barents Seas (Fig. 1). Litter was found in all transects and items larger than 5 cm were recorded from video recordings. This data set provides an overview of the distribution, density, and composition of litter over a wide area, covering depths from 50 to 2700 m and a variety of marine landscapes (Buhl-Mortensen and Buhl-Mortensen 2017, 2018). The density of litter decreased toward the north and with distance from the coast. In the Barents Sea, the mean density near the coast and offshore was 268 and 194 items km^{-2}, respectively. Litter was unevenly distributed in marine landscapes, and the density of litter on the deep-sea plain, continental slope, and shelf was typically below 200 items km^{-2}. Fjords and canyons harboured higher densities, indicating an accumulation effect in these areas. It is also clear that horizontal transport of litter along the seafloor should be considered. Depressions are likely not representative of the general density of litter and plastic but rather represent accumulation sites. Mapping programs such as Mareano can provide good background information for a designated seafloor litter monitoring plan.

Iceland is currently recording all bycatch of marine litter made as part of bottom trawl fish-stock assessments. More than 1000 annual stations of stock-assessment surveys are

Fig. 1. Map of regions within the AMAP region being monitored for litter on the seafloor or being visited once. Green squares: Mapping of the seafloor in the Mareano project (2006–2021). Red circles: Monitoring seafloor in the Fram Strait in the HAUSGARTEN project since 2002. Violet area: Recordings from bottom trawl from the Norwegian–Russian monitoring in the Barents Sea in 2019. This monitoring has been going on from 2010 to 2021, but the total area and number of stations can differ between years. Pink area and pink line: Recording in the Kara Sea and the Russian Arctic in 2019 (Benzik et al. 2021). Orange circle: Recordings from bottom trawls at the Kodiak Islands 1994–1996 (Hess et al. 1999). Green circle: Recordings at Iceland from bottom trawling as part of the bottom fish surveys and of the ongoing visual mapping of the seafloor. Purple circle: Mapping by video around the Faroe Islands in 2017. Base map source: Esri Boundary Layers (World). Coordinate system: WGS 1984 North Pole LAEA Europe.



used to register and classify marine litter (Fig. 1). In the Faroe Islands, marine litter is also recorded as part of an ongoing groundfish survey using bottom trawls. Dedicated seafloor mapping using video has also been conducted in several localities, and observed litter items have been recorded since 2015. In 2017, seafloor mapping using video surveys was started as part of the NOVASARC project (https://novasarc.hafogvatn.is/) and 60 localities were filmed (Fig. 1). In total, only 13 litter items were recorded during the 2017 survey, all of which were fishing lines (P. Steingrund, Faroe Marine Research Institute, pers. comm.).

The state of knowledge on marine litter, including microplastics, in the Arctic marine region primarily stems from information for areas where human activities are concentrated, including the Barents, Norwegian, and Bering Seas, or for specific research topics (e.g., seabirds). Few data are available for the Central Arctic Ocean and the coastal areas around it in Siberia, Arctic Alaska, mainland Canada, the Canadian Arctic Archipelago, and Greenland (PAME 2019). A compilation of some larger data sets on seafloor litter in the region covered by AMAP is presented in Tables 1 and 2 and illustrated in Fig. 1.

Table 1. Overview of seafloor litter reported from the AMAP area (see Fig. 1) including sampling gear, year, depth, size of litter recorded, number of samples, and total area covered. The percentage of samples with litter, together with the mean and maximum densities of the litter are provided as numbers and (or) weight. ROV refers to a remotely operated underwater vehicle. Data sources are indicated by numbers: 1. Hess et al. (1999), 2. Grøsvik et al. (2018), 3. Benzik et al. (2021). 4. Galgani and Lecornu (2004), 5. Parga Martínez et al. (2020), 6. Buhl-Mortensen and Buhl-Mortensen (2017), * = Estimated weight. n.a. = Not available.

Location	Alaska Kodiak Islands[1]	Barents Sea[2]	Siberian Arctic[3]	Hausgarten[4]	Hausgarten (Molloy Deep)[4]	Hausgarten[5]	Barents Sea[6]
Gear	Bottom trawl	Bottom trawl	Bottom trawl	ROV (0.1–1 km)	ROV (2 km)	Towed camera (1195–3570 m^2) transects	Video transect (1400 m^2)
Year	1994–1996	2010–2016	2019	1999–2003	1999	2002–2017	2006–2017
Depth (m)	<250	<500	n.a.	2284–3410	5339–5552	2300–2600	50–2700
Litter size (cm)	>2.5	>2.5	>2.5	>2	>2	>2	>5
No. of samples	625	1860	174	9	1	16 157 images	1132
Total area covered (km^2)	13.49	37.65	6.08	0.14	0.014	0.065	1.31
% samples with litter	32–38	33.5	13	100	100	1.42	27
Mean density (n km^{-2})	82 (coast) 22.3 (ocean)	n.a.	n.a.	271	1105	4571	268 (coast) 194 (ocean)
Maximum observed (km^{-2})	n.a.	n.a.	n.a.	460	n.a.	10 358	4400
Mean density (kg km^{-2})	n.a.	26	n.a.	n.a.	n.a.	n.a.	151*
Maximum observed	n.a.	1482	1320	n.a.	n.a.	n.a.	n.a.

Table 2. Existing monitoring programs on macro-litter on the seafloor.

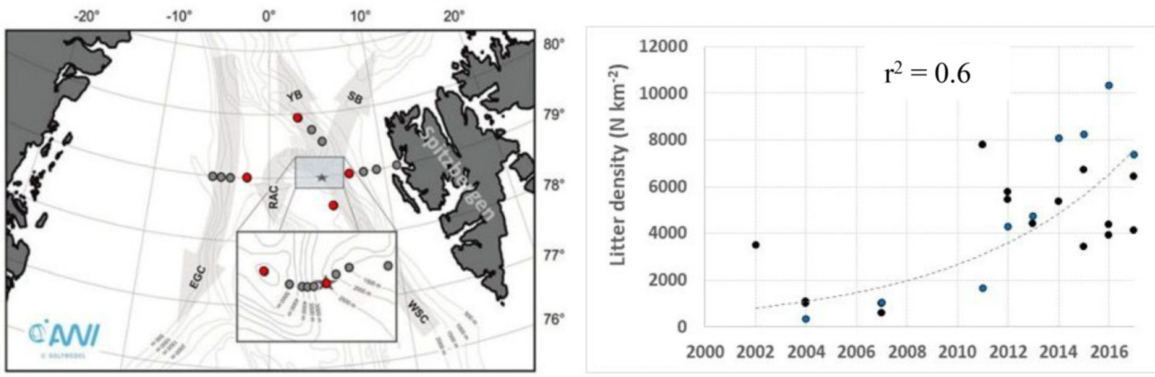
Region	Methods for recording	Frequency	Reference
Barents Sea	Bycatch from trawling	Yearly (since 2010)	Grøsvik et al. (2018)
Barents Sea	Video recordings	One time	Buhl-Mortensen et al. (2017)
Fram Strait	Video recordings, imagery	Yearly (since 2002)	Galgani and Lecornu (2004), Parga Martínez et al. (2020)
Russian Arctic	Bycatch from trawling	One time	Benzik et al. (2021).
Codiak Islands, Alaska	Bycatch from trawling	1994–1996	Hess et al. (1999)

4 Trends to date

In contrast to the constant levels of seafloor litter measured over time in studies performed in temperate areas (Galgani et al. 2021), measurements available for the Arctic appear to show an increasing temporal trend, suggesting increasing local activities (Parga Martínez et al. 2020) or a long-term transfer of marine litter from directly affected areas to regions where human activity is comparatively limited as recently modelled by Huserbråten et al. (2022). Data from the Russian–Norwegian Ecosystem Survey between 2010 and 2016 showed widespread pollution in the Barents Sea region, with litter found in 34% of the bottom trawl samples, yielding on average 26 kg km^{-2} of marine litter. Plastic accounted for 11% of the debris mass, and highest quantities were found in the southeastern Barents Sea (Grøsvik et al. 2018). The number of litter items recorded from bottom stations in the Barents Sea increased in the period that the measurements were conducted (2010–2018) (ICES 2019). Plastic was the dominant type of litter recorded to which fisheries-related items such as ropes, strings, cords, pieces of net, floats, and buoys contributed most (ICES 2019).

Plastic litter has also been sporadically recorded off the East Greenland slope (Schulz et al. 2010). In 2002, the HAUSGARTEN observatory was established in the eastern Fram Strait with 21 stations located at depths between 250 and 5500 m and has provided time-series data for litter (Bergmann and Klages 2012; Tekman et al. 2017). Analyses of still imagery from repeated towed camera transects conducted at three different stations located along a latitudinal gradient indicate an increase in litter on the seafloor from 2002 to 2017, with an initial strong increase in 2011 that was followed by elevated levels above 6000 items km^{-2} from 2014 onward (Fig. 2; Parga Martínez et al. 2020). The northernmost station, which is situated close to the marginal ice zone, harboured the highest amount of plastic litter and experienced the strongest increase from 346 to 7374 items km^{-2} between 2004 and 2017 (peak of 10 358 items km^{-2} in 2016), respectively. Glass was the predominant material type at this location. This is important as it points to local ship-based disposal because glass sinks directly to the seafloor due to the material's high density. However, at the central HAUSGARTEN station, the quantities of plastic also increased over time (~2500 items km^{-2}). If all three stations and years were combined, plastic accounted for 41% of the litter items. The use of imagery also allowed a rare assessment of marine litter impacts on benthic biota. Most frequently, litter was entangled in sponges (54%), followed by colonization of items by sea anemones (22%). There was an increase of litter entangled

Fig. 2. (Left) Location of sampling stations of the HAUSGARTEN observatory run by the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (Germany) since 1999 in the Fram Strait. Red circles indicate stations subject to repeated camera surveys (©T. Soltwedel, AWI). (Right) Litter densities recorded between 2002 and 2017 during camera transects undertaken at HAUSGARTEN. Blue circles reflect measurements from the northern station (redrawn with permission from data in Parga Martínez et al. 2020).



in sponges over time at the northern station, which affected 10% of the sponge population in 2015. At the northern station, up to 28% of the sponge *Cladorhiza gelida* Lundbeck, 1905 was affected, whereas at the southernmost station up to 31% of the sponge species *Caulophacus arcticus* Hansen, 1885 was entangled (Parga Martínez et al. 2020).

5 Strategies and methods for marine litter monitoring

The Arctic Basin is in a special situation in that it involves monitoring activities from different basins that are not connected except through the Arctic Ocean (Drinkwater et al. 2021). Consequently, monitoring of the Arctic Basin cannot be done without a harmonization of the different regional initiatives. Integrated monitoring of seafloor litter will require common strategies, approaches, and protocols shared by the International Council for the Exploration of the Seas (ICES) in the North Atlantic and North Pacific Marine Science Organisation (PICES) for the North Pacific, also linking with other regional action plans from the regional sea conventions such as Oslo-Paris Convention (OSPAR) for the Northeast Atlantic and Northwest Pacific Action Plan (NOWPAP). With European countries constrained by the EU Marine Strategy Framework Directive (MSFD), monitoring in the Arctic Basin may also take advantage of the work done previously in implementing monitoring in EU waters. However, monitoring is not only an assessment of trends but must also be able to assess the effectiveness of marine litter mitigation measures. For example, a ban on single-use plastics should be followed up by monitoring that can document robustly whether the quantities are decreasing on the seafloor. From a sampling perspective, the limitations of seafloor litter monitoring by trawling (Canals et al. 2021) highlight that such an approach must be underpinned with a statistically designed sampling strategy to be able to detect some % change in a short period of time (e.g., power analysis). This is often the case due to the large scale of the assessments, which can sometimes be oceanic scale. In addition, the proposed phasing out of trawling techniques for assessments of seafloor litter in future due to their highly destructive nature (ICES 2021) requires more adapted strategies. Visual census through the use of towed camera surveys, remotely operated underwater vehicles (ROVs), and submersibles are particularly suitable for the Arctic environment because of (i) few of large trawl-based fish stock assessment programs, (ii) issues may be more at the local scale, and (iii) conditions such as great depths, limit trawling operations. While SCUBA diving may be relevant at the local scale in shallower waters (e.g., harbours), this technique is only rarely used in the Arctic. The full potential of using imagery for monitoring purposes is yet to be realized, e.g., through improved data management, manual image analysis via new video annotation tools, deep-learning, and automated analysis methods. Camera surveys are particularly suitable to monitor rocky bottoms. In addition, visual census has an essential advantage as it can be used to collect data on the impacts of litter on the seafloor, especially entanglement (Galgani et al. 2018; Angiolillo et al. 2021) and will be used for monitoring of the indicator D10C4 of the MFSD on impact. The best strategy could be to monitor litter/epibenthic fauna interactions, characterized by strangulation, injury, coverage, and species colonizing litter items, which affects biodiversity. In addition, discussions have started among experts of the EU MSFD Technical Group on Marine Litter to focus on certain types of litter, e.g., on those for which mitigation measures are planned (i.e., single-use plastic, fishing gear). Finally, the strategy could be refined using opportunistic approaches that are well adapted to the context of Arctic regions.

Monitoring the seafloor will ultimately lead to questions regarding acceptable or critical levels of litter. In general, the Arctic is considered a possible reference area for all monitoring programs, including those in Europe (Werner et al. 2020). For seafloor litter, the approach will probably be very similar to those already implemented for the definition of baselines or thresholds (van Loon et al. 2020), to set future objectives. This will require compiling a large amount of data into a common database, establishing a strategy for setting baselines and thresholds, and choosing reduction targets to reach over time.

6 Benefits of monitoring

Time-series observations of the seafloor lend themselves particularly well to monitoring purposes as the seafloor represents a sink that integrates changes over longer timescales. In contrast, estimates from the sea surface can be considered snapshots in time, where litter can continue to be transported both spatially and to the seafloor, as well as being much more affected by weather, windage, currents, and mesoscale phenomena (van Sebille et al. 2020). Monitoring can provide information on temporal and spatial changes, litter quantity, and composition changes as well as impacts on species. This is critical for identifying when and where mitigation actions should be developed and implemented, especially if environmental levels can be linked to hazard assessment and overall environmental risk. Monitoring can also provide critical information about whether introduced mitigation measures are successful in reducing levels of litter or, perhaps even more relevant, slowing the rate of litter accumulation.

As in other environmental studies, seafloor litter assessment can be reported in a variety of dimensions, including size, weight, numbers, categories, and area (Galgani et al. 2013; Fleet et al. 2021). Bycaught litter from trawl surveys is often provided as weight. Additional recording of abundance and size allows comparability with data from visual census that can only record numerical abundance. Recording litter from bottom trawling has direct impacts on the seafloor being studied and is only recommended when performed as part of ongoing fish stock assessments. Both methods, trawl and visual census, come with their advantages and disadvantages, although data generated by the different approaches cannot be compared directly because of significant variations in sampling efficiency and the habitats covered. Advantages and disadvantages of the different methods are listed in Table 3.

7 Monitoring using imagery

Assessment at the HAUSGARTEN observatory was performed with a towed camera platform (OFOS, Ocean Floor Observation System), which was towed at a target altitude of 1.5 m for 4 h. Objects as small as 1–2 cm can be delineated, with smaller items are excluded. In recent years, the system has been further developed to provide both video and still imagery, although it is currently only the still images that are used for image analyses for the HAUSGARTEN time series. An important advantage of using cameras is that it shows litter items in situ such that interaction with biota can be analyzed. In addition, previous research has shown that deposition rates in the study area are quite low (Müller et al. 2012), meaning that items only become buried in the strata as deep as half a meter over centenary time scales. Still, they can be covered in a thin veneer of sediment relatively quickly, which can obscure detection. Nevertheless, this drawback can be considered minor compared to the benefits of covering a large area (1195–3570 m^2 per survey) and obtaining in situ glimpses of litter (Parga Martínez et al. 2020). Dedicated marine litter monitoring programs can be designed to specifically focus on seafloor areas known or predicted to be hotspots. Existing surveys deliver qualitative information on the composition of litter and how it changes over time.

8 Monitoring by documenting bycatch from trawling

Systematic spatially distributed investigations using trawls, which aimed to facilitate determination of sources and accumulation were first published in 2000 (Galgani et al. 2000; Moore and Allen 2000). Aided significantly by the cost-efficiency of piggybacking on ongoing trawl programs, standardized monitoring protocols have produced marine litter time series that allow trend analyses covering the last ∼20 years (Maes et al. 2018). Most European countries record litter items in catches as part of other environmental monitoring activities, e.g., the ICES International Bottom Trawl Surveys (IBTS) (Moriarty et al. 2016) and the International Bottom Trawl Survey in the Mediterranean (MEDITS) (Bertrand et al. 2002; Fiorentino et al. 2017). Litter bycaught in trawls has been recorded at least since 1994 (Table 1).

9 Fishing for litter

Fishing for litter (FFL) is an initiative that invites fishing vessels to reduce marine litter by collecting litter including lost fishing gear and delivering it safely to harbours that have established agreements to receive such waste. A pilot FFL action ran in the Faroe Islands during 2008 and has recently been restarted with four trawlers participating. It was reported that plastic constituted 95% of the litter collected (https://fishingforlitter.org/faroe-islands/). The Norwegian Environment Agency established a national FFL scheme in 2016/2017, which began with three participating ports (http://fishingforlitter.org/norway/) and has built up to currently 11 ports and 101 vessels that have collected 743 tonnes of litter. The Norwegian national FFL scheme is administered by SALT Lofoten AS in collaboration with Nofir, the local ports, and waste management companies.

10 Existing monitoring of litter in the Arctic

The joint Norwegian–Russian Ecosystem Survey in the Barents Sea is performed annually in August–October and comprises approximately 300 sampling stations. The survey includes the sampling of several fish species, shrimp, and sediments for resource mapping where monitoring contaminants are included for selected species. Floating debris and litter as bycatch in trawls are also recorded. Between 100 and 200 stations may be recommended to cover plains and landscapes in a representative way based on experiences from the Mareano mapping, although statistical analyses may be the best basis when planning the number of stations. In addition to time series of litter on the seafloor, the HAUSGARTEN observatory work also includes regular sampling of deep-sea sediments for microplastic analyses (Bergmann et al. 2017*a*; Tekman et al. 2020). It also includes occasional surveys of the water column, sea ice, snow (Bergmann et al. 2019; Tekman

Table 3. Various methods to monitor macrolitter on the seafloor and the advantages/disadvantages to each method.

Method	Advantages	Disadvantages
Bycatch from trawling	• Ability to generate physical samples for detailed inspection and analysis. • Assessments can be conducted with low logistic effort and cost if implemented as part of ongoing stock assessments.	• Recording litter from bottom trawling has direct impacts on the seafloor being studied and is only recommended when performed as part of fish stock assessments. • Trawling is limited to sedimentary habitats and certain depths. • Results dependent on sampling gear and the design of the fish stock assessment surveys. • Differences in selectivity among gears, vessel speed, mesh size, cod ends (narrow ends of tapered trawl), and methods used among countries and regions, observers, and studies. • Trawls must be considered semiquantitative because they may not be in constant contact with the seafloor.
Imagery	• Because of its unobtrusive nature, visual census allows for observations of litter in vulnerable ecosystems and provides detailed information on litter position in the marine landscape. • It shows litter items in situ such that interaction with biota can be analyzed.	• Visual seafloor mapping typically reports the number of items per area for different litter categories, and weight can only be estimated.
Video recordings	• Same as imagery.	• Same as imagery. • Footage of ROVs with a forward-looking camera with an oblique angle to the seafloor can only provide data per linear metre, which hampers comparability with data given per unit area.
Diving	• Same as imagery. • Precision surveys in a hidden part of the sea floor (holes, under rocks, etc.). • Can be used opportunistically in surveys in addition of regular monitoring of biodiversity	• Only coastal (depth limitation). • Not everywhere in the Arctic (temperature may not allow long surveys).

et al. 2020), and zooplankton (Botterell et al. 2022), as well as macrolitter surveys at the sea surface and on the beaches of Svalbard (Bergmann et al. 2016, 2017*b*; Tekman et al. 2022).

11 Recommendations

For monitoring purposes, it is recommended that seafloor litter is documented both from imagery recording or through trawling if part of an ongoing fisheries stock assessment. Data should be presented in as many dimensions as possible using standardized methods to allow for a broad international comparison of seafloor litter densities and composition. Table 1 highlights the vital importance of the sampled area for comparisons to be possible. Our first level recommendations are to develop an Arctic monitoring plan for seafloor litter (>2 cm) by selecting representative sites for visual census that will cover different depths and substrata in marine landscapes. We also recommend recording litter that is collected or observed in all sampling of seafloor habitats (bycatch from bottom surveys, SCUBA diver observations, camera surveys, etc.) and to perform studies that give information on gear uncertainty and between gear uncertainty. For the second level, representing "should do/develop", we recommend developing more automated and autonomous ways to record and analyze litter on the seafloor, for example, by use of artificial intelligence. For future research, it is important to improve optics and automated image recognition for litter quantification to overcome the bottleneck of time-consuming manual image analyses. Alternative monitoring approaches should be investigated, including digital and autonomous techniques that have the potential to overcome temporal and spatial gaps in existing approaches and data sets.

Data recording and management should be via an online, international database system controlled by local managers. Regional/country coordinators would then review and approve uploaded data. This would ensure consistency within each region and create a hierarchy of quality assurance of the data acquired. For recording litter from the seafloor, we recommend following the EU MSFD Guidance on Monitoring of Marine Litter in European Seas (Galgani et al. 2013) using the joint list of litter categories (Fleet et al. 2021) and online photo catalogue (https://mcc.jrc.ec.europa.eu/main/photocatalogue.py?N=41&O=457&cat=all).

Box A: Standard metrics that should be reported for all studies examining marine litter on the seafloor.

Must-have data for reporting seafloor litter

- Location, including latitude and longitude
- Depth
- Date, including day, month, and year
- Sample method (trawl type, mesh size, opening size, ROV, video, still camera, SCUBA diving surveys), speed, distance, altitude, sampled area, minimal size limit
- Hydrographic data
- If multiple transects are run at any given site (replicates)
- Primarily number and if possible weight (volume) per square kilometre
- Data (abundance or density, mass or size) should be reported as mean, median, minimum, and maximum
- Category, material, source
  - Photo cataloging/photo documentation (according to the EU MSFD joint list of litter categories (Fleet et al. 2021) and the online photo catalogue of the joint list of litter categories (https://mcc.jrc.ec.europa.eu/main/photocatalogue.py?N=41&O=457&cat=all)).
- Data recording and management should be via an online, international database system controlled by local managers.

Beneficial to have

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

As illustrated in Fig. 1, we need better coverage and knowledge of status of seafloor litter for the whole Arctic and recommend such initiatives to be taken for regions where such knowledge is lacking.

More data and understanding of levels and trends from the Central Arctic Ocean and the coastal areas around it in Siberia, Arctic Alaska, mainland Canada, the Canadian Arctic Archipelago, and Greenland would be important for assessments of transport and pressure of litter at the seafloor in the whole Arctic.

12 Quality assurance/quality control

A summary of “must have” and “beneficial to have” data needs for seafloor litter monitoring is presented in Box A. For the IBTS, sampling data are collected in the ICES DATRAS database and are subjected to data quality checking for hydrographical and environmental conditions. This process could also support quality assurance for seafloor litter data. One of the major issues related to marine litter monitoring is ensuring a robust and reliable identification and categorization of litter items. In this respect, available guidance documents from organizations such as the EU MSFD Guidance on Monitoring of Marine Litter in European Seas (Galgani et al. 2013) and ICES (2021) should be followed. These seafloor litter guidance documents contain information about sampling, data reporting, and quality assurance/quality control, including the definition of litter categories and subcategories. As a recent development of these guidelines, a joint list of litter categories has been developed in collaboration within the context of the EU MSFD (Fleet et al. 2021). An online photo catalogue of the joint list of litter categories is also available (https://mcc.jrc.ec.europa.eu/main/photocatalogue.py?N=41&O=457&cat=all).

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