Emerging Contaminants 5 (2019) 308–318

Contents lists available at ScienceDirect

Emerging Contaminants

journal homepage: http://www.keaipublishing.com/en/journals/emerging-contaminants/

Plastic litter in the European Arctic: What do we know?

Claudia Halsband [a], [*], Dorte Herzke [b]

[a] Akvaplan-niva, Fram Centre for Climate and the Environment, N-9296, Tromsø, Norway
[b] The Norwegian Institute for Air Research, Fram Centre for Climate and the Environment, N-9296, Tromsø, Norway

ARTICLE INFO

Article history:
Received 20 December 2018
Received in revised form
31 October 2019
Accepted 1 November 2019

Keywords:
Arctic
Litter
Plastic
Distribution
Biota
Ecosystem
Review

ABSTRACT

Despite an exponential increase in available data on marine plastic debris globally, information on levels and trends of plastic pollution and especially microplastics in the Arctic remains scarce. The few available peer-reviewed scientific works, however, point to a ubiquitous distribution of plastic particles in all environmental compartments, including sea ice. Here, we review the current state of knowledge on the sources, distribution, transport pathways and fate of meso- and microplastics with a focus on the European Arctic and discuss observed and projected impacts on biota and ecosystems.

1. Introduction

Plastic pollution in general and especially in the oceans has emerged as a major environmental problem world-wide, and has been recognized as a threat to all ecosystems. Large amounts of plastic waste are generated globally every year [1], relating to the high and further increasing annual production rates. In the 1950s, at the onset of plastic mass production, less than 2 million tonnes were produced per year, increasing to hundreds of millions of tonnes today (2016: 335 million tonnes) [2]. Recent estimates predict that 5–12 million tonnes end up in the oceans every year [1]. Mismanaged waste from coastal cities entering large rivers, and insufficient waste water treatment, are main entry routes for plastic litter into the oceans, from where the debris is carried with the ocean currents [3,4]Atmospheric distribution with the winds also plays a role for long-range transport, particularly for the smallest plastic particles [5]. From industrialized and highly populated areas, plastic litter spreads in the environment at global scale [6]. It also reaches the remote and seemingly untouched Arctic Ocean [7]. The Arctic is highly connected with adjacent seas, e.g. through the Fram Strait, the Bering Strait and the porous Alaska Archipelago, and the propagation of plastic litter thus extends into the Arctic.

First reports on plastic pollution in the Arctic date back to the 1970s. Merrell (1980) described observations of marine plastic at ten 1 km long stretches of beach on Amchitka Island, a 65 km long and 5 km wide Aleutian Island in the Bering Sea [8]. The intertidal zones of the beaches were surveyed once a year for three years, where the number of total litter items increased from over 2200 to more than 5300 in a two-year period (1972–74). The accumulation rate by weight was nearly 60% per year, and most litter originated from fishing vessels, but some items had travelled more than 1000 km from the Asian coast, demonstrating long-range transport for the first time.

To understand the transport of plastic litter into the Arctic (defined here as the Arctic boundary according to the Arctic Monitoring and Assessment Programme by the Arctic Council), regional distribution patterns within the Arctic and temporal trends, knowledge of local sources and their contributions to plastic pollution within the Arctic are of importance, but also an understanding of the sources and transport pathways from more densely populated areas further south is required. Depending on their size, composition, density and shape, plastic particles may accumulate in various arctic environmental compartments on land and at sea, i.e. in soil or vegetation, in the water column, in or on seafloor sediments, and in littoral zones. A basin-scale litter patch has been predicted for the Barents Sea, based on calculations from drifter

---

[*] Corresponding author.
E-mail address: clh@akvaplan.niva.no (C. Halsband).
Peer review under responsibility of KeAi Communications Co., Ltd.

https://doi.org/10.1016/j.emcon.2019.11.001

buoy data [9], but to date has not been observed in situ. If the Arctic represents a global sink of plastic pollution [10] or a source of microplastics upon melting of Arctic sea ice containing a legacy of microplastic deposits from the past decades in the context of climate change [11,12] is a matter of debate.

This review is based on the recent Arctic Monitoring and Assessment Programme (AMAP) report on ‘Contaminants of Emerging Arctic Concern’ [13] where we summarized information available for the occurrence, pathways, and impacts of plastic pollution in the arctic region, with a focus on the European Arctic, and reference to information from subarctic regions (50–70°N) where relevant.

Since the early 2000s, scientific interest in plastic pollution has increased dramatically, suggesting ubiquitous occurrence and broad impacts of plastic in the environment. Initially, most studies focused on marine ecosystems [14] but more recently also freshwater systems [15,16] and terrestrial systems [17] have received attention. The data presented here include peer-reviewed publications and international reports with well-described methods, based on a literature search in the Web of Science Core Collection and PubMed (accessed on 17th Dec 2018 and 3rd June 2019) with the following search terms: microplastic AND Arctic; marine plastic litter AND Arctic; plastic pollution AND Arctic; ingested plastic AND Arctic in the databases of PubMed and Web of Science Core Collection. No anecdotal data were included.

2. Properties and behaviour of plastic litter in arctic environments

2.1. Oceanic plastic transport into the Arctic

As most human activities resulting in potential plastic emissions occur in the industrialized parts of the world, a major proportion of plastic litter in the Arctic can be assumed to be transported into the region from further south, and mostly with the ocean currents. Zarfl and Matthies (2010) attempted to estimate the flux of organic pollutants through absorption into plastic debris to the Arctic. Estimates of plastic flux to the Arctic ranged from 62000 to 105000 tons per year, subject to spatial and temporal variability and bias from sampling methods [18].

In a global modelling study, the distribution and transport of plastic debris was predicted using observational data from the drifter buoys in a particle-trajectory tracer approach on time scales of years to centuries [9]. The model predicted six major garbage patches, one in each of the five subtropical basins and one patch in the Barents Sea. In this exercise the connectivity between the basins was high at centennial time scales and a significant amount of the debris eventually accumulated in the North Pacific patch, which seems to be the main attractor of global marine debris over long time scales (millennia). The role of the Arctic patch for global plastic distribution needs to be confirmed and validated with empirical evidence, but comprehensive and regular monitoring of the large and remote Arctic region is challenging.

The speed of horizontal transportation of macro- and microplastics is different, where large buoyant debris is exposed to wind stress, while microplastics are completely submerged. The transport of submerged marine debris from the Tohoku Tsunami was predicted to reach the International Dateline after six months and then slow down to 5 cm/s, the speed of the north Pacific current [19]. In addition, the physical and chemical properties (e.g. boiling point, vapor pressure, water solubility and octanol-water partitioning) of the monomers and additive ingredients in addition to properties of the polymers themselves (e.g. size, shape and pore size) are important when assessing their environmental fate [20].

2.2. Physical-chemical properties

Plastic debris consists of complex organic polymer materials and many different chemicals, manufactured according to the needs of their intended use. Several size classes of plastic particles are commonly distinguished [21]: mega (>1 m), macro (1 m–25 mm), meso (25 mm–5 mm) and micro (<5 mm). As in other regions, the entire size range of plastic debris is also found in the Arctic, from large macro debris, often from fishing activities [22] to small microplastics and fibers, where the smallest microplastics dominate in abundance [23]. Plastics in the smallest category, nano (<1 μm), are to date not studied in Arctic systems.

Plastics are semi-persistent and slowly break down to smaller particles, eventually reaching micro- and nano-scale (see 1.4 below). Most polymers used in common consumer products, such as polypropylene (PP), polyethylene (PE) and polystyrene (PS), have lower densities than water, and thus float on seawater. This provides a pathway for entrainment in arctic sea ice. Higher density polymers such as Polyvinyl chloride (PVC) and polyethylene terephthalate (PET) will more easily deposit in terrestrial soils and sink to the seafloor in marine systems [24]. In the ocean, the physics of moving water masses and interactions with marine microorganisms complicate the behaviour of the plastic. Low-density materials can remain in the sea surface microlayer (upper few millimeters), although wave and wind action can alter patterns of mixing and temporarily submerge them. In estuarine habitats, low density plastics may become submerged in hydrographic fronts with varying salinity and density. Colonization of bacteria and microalgae and subsequent accumulation of more diverse biofilms may also affect the weight of the litter, causing it to sink [25].

2.3. Sources

Pinpointing the sources of plastic debris and especially microplastics is often difficult, as the point of entry into the environment is often unknown, and the nature of the original plastic products can only be inferred from shape, polymer type and – where analysed – the combination of additives such as plasticizers, colour etc.

Plastics can be released locally into the arctic environment during industrial activities (e.g. fishing, shipping, aquaculture and tourism, Fig. 1a), but also from domestic sources (e.g. washing of synthetic textile clothing, personal care products containing microplastics, e.g. tooth paste, exfoliators etc.). Type and intensity of arctic industrial activities (Fig. 1a) and population changes along arctic coasts (Fig. 1b) represent local drivers of plastic pollution in the Arctic. Increasing urban populations in the European sector, Canada and Alaska will generate more plastic waste than decreasing populations in the rural areas along the Russian coasts, creating hot spots of plastic litter input into the Arctic. How much plastic enters the Arctic environment from land depends not least on the local and regional development, and implementation of appropriate waste disposal and recycling facilities – or the lack thereof. Infrastructure, such as waste water treatment plants, is often absent in sparsely populated Arctic regions [26].

In addition to local sources, long-range transport from temperate regions to the Arctic in both atmosphere and ocean currents are important transport pathways, but to date little understood. Transport with ocean currents from populated areas further south is highly likely [26], 51]. Large amounts of Atlantic water enter the Arctic Ocean through the Fram Strait and contain variable amounts of plastic items and microplastics [27]. Recent reports also demonstrate the role of air and precipitation for the transport of microplastics [5] particles, explaining the presence of microplastic in arctic snow and ice samples [7, 12, [12,28].

Discerning local inputs from contributions coming from more

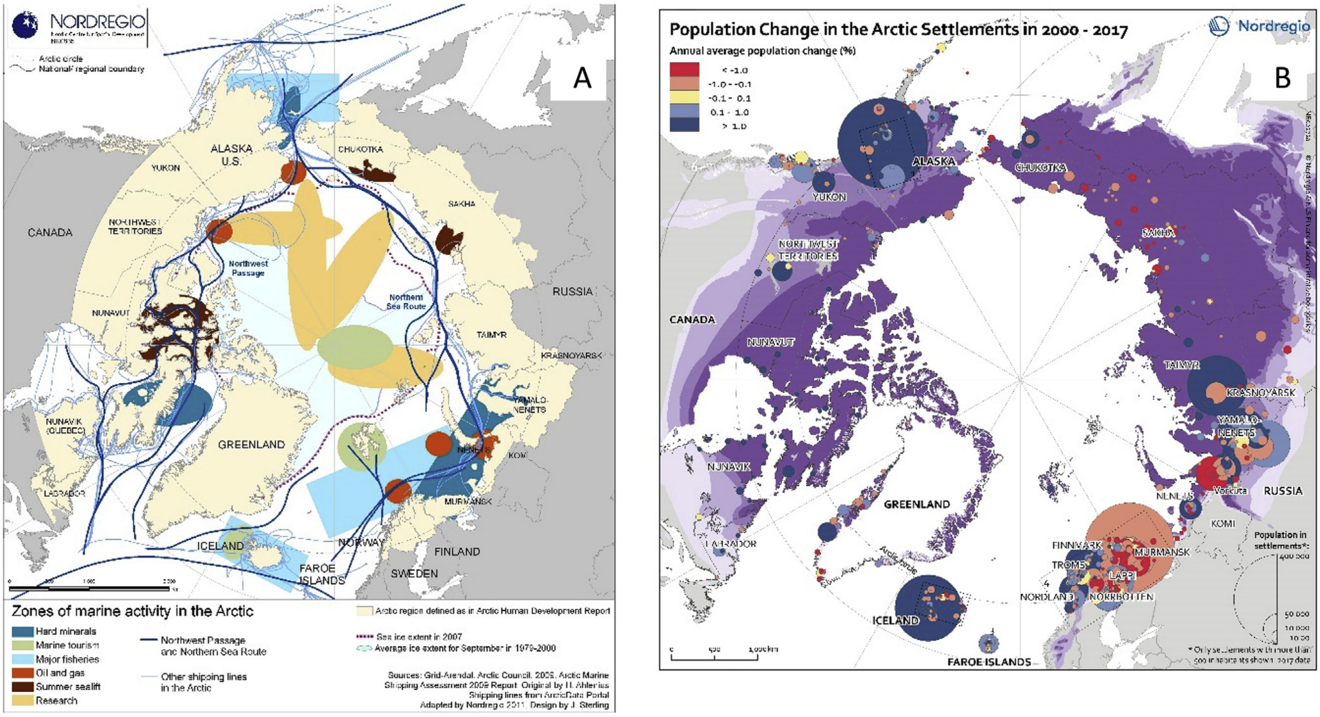

Fig. 1. a) Arctic industrial activities (from: ArcticData 2011); b) population change in Arctic Settlements in the period 2000–2017 (NordRegio 2018).

densely populated areas further south (through long range transport) is challenging, but important, in order to predict plastic pollution distribution and hot spots in the Arctic and implement effective mitigation and prevention measures.

2.4. Transformation processes

Transformation and weathering of marine plastic can occur along several routes. Although these processes are similar throughout the global environments, they may function differently under arctic environmental conditions than in temperate regions, altering processes such degradation and sedimentation rates and thus net fluxes of plastic particles through different environmental compartments including food chains. As specific information on arctic transformation processes is at present unavailable and represents an important knowledge gap, we describe these in general terms, since they are nonetheless relevant also for arctic habitats. Pathways for degradation of marine plastic were recently reviewed [12,28]. Plastic items are broken down into smaller particles through mechanical abrasion, hydrolysis or photodegradation through UV from sunlight. Increasing brittleness promotes breakdown of the polymer structure, but degradation rates are slow [20,27], especially under cold arctic temperatures. Biodegradation is another pathway, where microorganisms directly convert polymers containing heteroatoms into new biomass and a range of chemicals. For example, high density polyethylene (HDPE) showed an altered surface topography, colour, and new functional groups upon weathering [29]. In how far the specific arctic conditions, with long phases of continuous UV exposure during the Arctic midnight sun versus extremely low temperatures without any UV radiation during the arctic winter, alter degradation processes has not yet been investigated. Biofouling, i.e. colonization of the plastic by microbes, may lead to mechanical erosion of the surface. Similar to all these processes is that they start on the surface of the plastic particle, such that the material becomes brittle and porous. Colonization by microbes and larger rafting organisms also alters the properties of the plastic material and its behaviour in the environment. Latitudinal trends, however, show that only a small proportion of plastic fragments is colonized at latitudes >60°N, e.g. by barnacles and bryozoans [30,31]. Latitudinal differences in biofilm properties and species composition may therefore be a driver of plastic pathways and fate. Ingestion by a variety of animals and subsequent egestion in fecal material repackages, transports and accumulates plastics and microplastics in various pathways, depending on size, ingesting animal and type of faeces [32,33]. Experimental ingestion of microplastics by marine zooplankton usually leads to egestion of the plastic particles in faecal pellets, which enwraps them in an organic coating, and in turn can be taken up by detritus feeders [34] but these processes have not been observed in situ. Biofouling on the plastic surface can increase the selection of plastic particles as food items [35,36]. The repackaging in fecal matter also changes the buoyancy and thus sinking behaviour of the plastic and aids re-suspension and vertical transport both up and down in the water column, e.g. as part of marine snow [37]. Another example for a biological transformation from macro to microplastics is the burrowing activity of boring invertebrates, which have been shown to use plastic structures as a substrate, and can release thousands of microplastics per burrow [23]. An increasing number of coastal and offshore installations (e.g. aquaculture facilities) with submerged plastic structures in arctic locations will increase the chances for such transformation processes to occur in arctic waters.

2.5. Plastics as carriers of chemicals

Plastics are able to adsorb persistent organic pollutants (POPs). If such chemicals are present in the surrounding sweater, the plastic can act as a vector for surface active hydrophobic contaminants such as polychlorinated biphenyls (PCBs) and brominated flame retardants (BFRs) [38]. Sorption is expected to increase as the plastic weathers and available surface area increases [39]. PE and PP adsorb the highest number and amounts of polyaromatic hydrocarbons (PAHs) and PCBs [40–42]. Additives are often important constituents of plastics and represent high proportions of the material. They can leach out of the plastic particles over time, since they are not chemically bound to the polymer. These processes warrant further investigation under acrtic conditions. The mass fluxes of polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and perfluorooctanoic acid (PFOA) in plastics transported to the Arctic with the main ocean currents were compared with those in the dissolved phase and in air [18]. The calculated mass fluxes of the chemicals studied were four to six-fold higher in air and the ocean water, such that plastic seems to play a minor role in transporting these compounds northwards.

3. Environmental concentrations of plastics in the arctic

3.1. Air & precipitation

Few published data are available on plastics and microplastics in air and precipitation in arctic regions. Atmospheric transport of plastic particles has been observed in the cities of Paris (France) and Dongguan (China) [43,44], but also to remote areas [5]. The role of air and precipitation in transporting plastic particles to the Arctic was highlighted when microplastics were detected in snow samples from ice floes in the Fram Strait and from snow collected on Svalbard [38]. A quantification of transport rates and routes is, however, not yet available.

3.2. Terrestrial environment

Despite many anecdotal accounts of plastic pollution and wildlife entanglement in arctic terrestrial habitats in the media and popular science outlets, no systematic approach to quantifying plastics and microplastics in the terrestrial environment has been performed to our knowledge, indicating an important knowledge gap [45].

3.3. Freshwater environment

The current knowledge of microplastics distribution and impacts in fresh water systems has recently been reviewed, where the scarcity of data on the distribution, transport and effects of plastics on biota has been highlighted [16,46]. No data from Arctic freshwater systems exist to date. Various similarities with marine environments can be expected in terms of sources, transport with currents, ubiquity of plastic particles in the system, and potential impacts on biota. A main difference is the typically smaller size of freshwater systems and shorter residence time of water in these systems, and as a result, different spatial and temporal patterns in the physics of the transport and mixing of plastic particles in the water column [47]. For benthic systems, Corcoran (2015) describes the pathways of plastic litter from land to freshwater/brackish benthic systems has been described, and the controlling parameters are similar in both marine and freshwater, i.e. proximity to human point sources, riverine input, geomorphology of the basin, and the behaviour of water circulation are determining factors for plastics distribution and fate [48]. However, it is clear that this is an important knowledge gap in the Arctic, where specific information for rivers and lakes is lacking and the strong seasonal cycle with frozen lake surfaces for large parts of the year and melting activity in the summer will have an impact on plastic dynamics.

3.4. Marine environment

Most information about arctic plastic pollution concentrations currently available comes from the marine environment, covering both abiotic and biotic samples. Monitoring efforts in arctic regions are scarce due to difficult logistics in the harsh conditions such as sea ice cover, and only few scientific reports exist from the central Arctic Ocean and arctic sea-ice ice [12,49,50]. A collaboration between Norway and Russia has documented marine litter, including macroplastic, in the Barents Sea [22]. Highest plastic litter concentrations were recorded along the major ocean currents in areas of intensive fishery and shipping activity. Plastic debris was recorded at the surface, in the water column, as well as on the seafloor, with the largest number of items in pelagic trawls.

3.4.1. Water column

Macroplastics were observed floating on the sea surface and enumerated by visual observations during helicopter surveys in Fram Strait [27]. Although 37% of the net samples were plastic-free in a circumpolar sampling approach, up to 323 microplastics per net tow were recorded in the Greenland and Barents Seas, extrapolating to a maximum of 133,815 particles/m^2 and 1200 tons total load [10]. The authors postulate that the Arctic is a dead end for microplastic due to the enclosing land masses and prevailing thermohaline circulation, eventually resulting in vertical deposition towards the seafloor. Off the coast of northeast Greenland 2.4 particles/m^3 ±0.8 SD were observed in water samples [51]. Systematic sampling of the water column conducted between Tromsø, Norway, and Svalbard, up to a latitutde of 78.08°N revealed ubiquitous occurrence of microplastics in >90% of all samples from these waters [52]. The average concentration sampled with a Manta net was 0.34 particles/m^3, while subsurface sampling with the ship's pump, at 6 m depth, resulted in average particle counts of 2.68 particles/m^3, demonstrating the difference between different sampling methods. These results are comparable with other studies around the world and slightly higher (but not statistically significant) than concentrations estimated with the same method in the North Atlantic [53]. In the North Pacific, significant amounts of microplastics were found in the water and inside zooplankton [54,55]. It is likely that such patterns also occur further north in the Pacific sector of the Arctic, and that the Arctic may not be less polluted with microplastics than regions at lower latitudes. Subsurface microplastics distribution was studied between 8 and 4369 m depth [50]. The median microplastic abundance near the surface was 0.7 particles/m^3. The Polar Mixed Layer had the highest concentrations of plastic particles ranging from 0 to 375 particles/m^3, while the deep and bottom waters contained up to 104 particles/m^3. Atlantic water had lower particle concentrations (0–95 particles/m^3), and the halocline the lowest (0–83 particles/m^3). Similar concentrations were reported from sub-surface water off the coast of northeast Greenland, averaging 2.4 particles/m^3 ±0.8 SD [51].

3.4.2. Seafloor

Observation of the deep arctic seafloor [27] revealed densities of plastic debris of 7710 particles/km^2, comparable to those observed in the deep northern Gulf of Mexico [56] and even higher than quantities reported from marine canyons close to Lisbon (6600 particles/km^2), which were classified as moderately [57]. Distribution and composition of sea bed litter was mapped in regions of the European Arctic and Subarctic in >1700 video transects. Litter was found in 27% of observations with on average 202 and 279 particles/km^2, respectively, but the most polluted areas exceeded the average values for Europe. High quantities of microplastics were also reported in Arctic deep-sea sediments (at 2340–5570 m depth) from the HAUSGARTEN Observatory in Fram Strait (42–6595 particles/kg) with the northernmost stations containing the highest quantities [23]. In the Barents Sea mean levels of plastic of 2.9 kg/km^2 were reported at the sea floor. Average levels of marine litter (all material types) were 26 kg/km^2 [22].

On the Pacific side, high levels of microplastic contamination were found in the northern Bering Sea, and especially in the Chukchi Sea [58]. The average number of items found was 22.8 particles/kg dry weight, consisting mostly of fibres between 0.1 and 5 mm length. Further during the German-Russian expedition KuramBio (Kuril-Kamchatka Biodiversity Studies) to the northwest Pacific Kuril-Kamchatka Trench and its adjacent abyssal plain m microplastics were ubiquitous in the smaller fractions of the box corer samples from every station from depths between 4869 and 5766 m [59].

3.4.3. *Sea ice*

High concentrations of microplastics in arctic sea ice were found in a study on multi-year ice with up to 250 particles/m^3 in sea ice cores collected at several sites across the Arctic Ocean [11]. The polymers found in various shapes and colors were rayon (a manmade semisynthetic, 54%), followed by polyester (21%) and nylon (16%), polypropylene (3%), and 2% each of polystyrene, acrylic, and polyethylene. Sea ice cores may thus be a valuable retrospective record of the historical deposition of plastic litter in the Arctic, both from marine and atmospheric sources. Small-scale horizontal microplastic distributions revealed unique patterns and polymer composition in drifting sea ice [12]. Continuous melting of sea ice in the context of climate warming will release these particles back into the water column, potentially presenting a major future source of plastic pollution southward via the arctic outflow regions.

3.5. *Littoral zone*

One of the longest time series for plastic litter in the European sector of the Arctic is hosted by OSPAR (the Convention for the Protection of the Marine Environment of the northeast Atlantic), which includes monitoring of plastic litter on beaches in Europe since 2001 [60], where arctic locations were included in 2011, e.g. in northern Norway and Svalbard. This data set provides data for the litter composition in various locations, where arctic waters are dominated by plastic fragments and show the highest proportion of fishing-associated debris (Fig. 2). At two arctic locations, one on the mainland and the other on the north-west coast of Spitsbergen, several types of litter were found, such as different kinds of plastic items (bags, boxes, buckets, helmets, nets, trawls), pieces of cardboard, metal and glass, clothing, wood, and pieces of rubber. On a beach length of 100 m in Rekvika, (northern Norway), the number of plastic pieces varied between 2670 and 12928 items, which were collected between 2011 and 2017 (Fig. 3) [60]. For comparison, the average number of all plastic items found on 100 m of beach in Brucebukta (Svalbard) was much lower (approximately 200 items, Fig. 3). In a citizen science approach, 6 beaches on Svalbard (including Brucebukta) were surveyed along the western and northern coasts. In this study, between 9 and 524 g/m^2 litter were recorded in 2016. The proportion of plastics was >80% of all litter. In Brucebukta this equated to 17.9 g/m^2, and most items stemmed from fishing activities (11.1 g/m^2) [61]. Due to the different methods of quantification (number of items per beach length versus mass per area) the two data sets for arctic beaches, including Brucebukta, cannot be directly compared.

Different items were also found at the Icelandic coastline, such as plastic bags and other plastic, buoys, fishing nets, building material, driftwood and other wood pieces. Possible land-based sources for the observed litter are tourism and recreational activities in addition to commercial fisheries and shipping. Although there has been no research on the origin of marine litter, an estimate of the project “Fishing for Litter” on the Faroer Islands indicates that land-based sources, such as municipal waste management systems, rivers, tourism and recreational activities are likely direct input sources. Fishing boats and the fishing industry in general, as well as other maritime transport, are the principal sea-based sources for the European Arctic seas, including offshore oil/gas installations. In Norway, the aquaculture industry contributes significantly on a local scale; and in certain areas up to approximately 30% of the total amount of marine litter [60].

In Alaska, marine debris was found at all 28 beaches surveyed. Hard plastics were found on every beach and foam was found at every beach except one. Rope/netting was the next most commonly found category, present at 23 beaches. Overall, plastic contributed to 60% of the total weight of debris [62].

Variations in the amount of observed marine litter on beaches between locations and years are owed to variations in weather conditions and seasonal hydrography, in addition to potential singular loss or dumping incidents on vessels and offshore installations.

3.6. *Arctic biota*

Seabirds have been used as biomonitors of pollution for many years, and many arctic seabird colonies are well studied. As a result, a number of reports on plastic ingestion by birds exist [63,64], and some of the longest time series on environmental plastic contamination come from seabirds, including some arctic locations in Canada, northern Iceland, the Faroer Islands and Svalbard [65]. Dietary studies of birds from the Canadian and European Arctic have reported ingestion of plastics, especially by the northern fulmar *Fulmarus glacialis* [66–69]. The northern fulmar is a surface feeding seabird with an extensive foraging range over offshore areas during its entire lifecycle. This makes it an ideal monitoring sentinel for marine plastic litter [68,70–72]. The plastic load in beached dead fulmars is monitored annually as a contribution to Ecological Quality Objectives (EcoQO) monitoring implemented by OSPAR [72]. Plastic ingestion of northern fulmars has been described in several arctic regions [73], where birds with >0.1 g of plastic items in their stomachs declined in number along a south-north gradient. Also other seabirds are reported to ingest plastics, but to varying degrees, where surface-feeders such as kittiwakes and fulmars are more prone to plastic ingestion than pursuit diving murres and black guillemots [74]. Arctic seabirds transport marine-derived contaminants into the Arctic [72], some of which may come from plastic, while more recently plastic has been found in seabird guano [33], showing a route of entry for both the plastic itself and associated contaminants into arctic environments [75,76]. The origin of contaminants is, however, difficult to determine, as it depends on both background contamination levels in the surrounding environment at the time of exposure and in prey organisms [77]. Fulmars from Svalbard showed that 88% of the 40 examined fulmars had ingested plastic, averaging 0.08 g or 15.3 pieces per individual, where 22.5% exceeded OSPARs EcoQO [67]. Further south, on the north Norwegian mainland (Finnmark), 36% exceeded the EcoQO threshold (N = 75), and 81% of all investigated individuals contained ingested plastic. The particle size varied between 1.8 mm and 9.1 mm (mean 5.0 mm) in addition to some longer threads. Of 20 subsampled individuals, an average of 0.2 g or 24 plastic pieces were found with a maximal number of 106 plastic pieces [77]. Similarly, 79% of fulmars had ingested plastics in the Labrador Sea, with on average 11.6 pieces or 0.151 g plastic found in the stomach per bird [68]. At the more regional scale, the north-sound plastic contamination gradient appears to be steeper in the

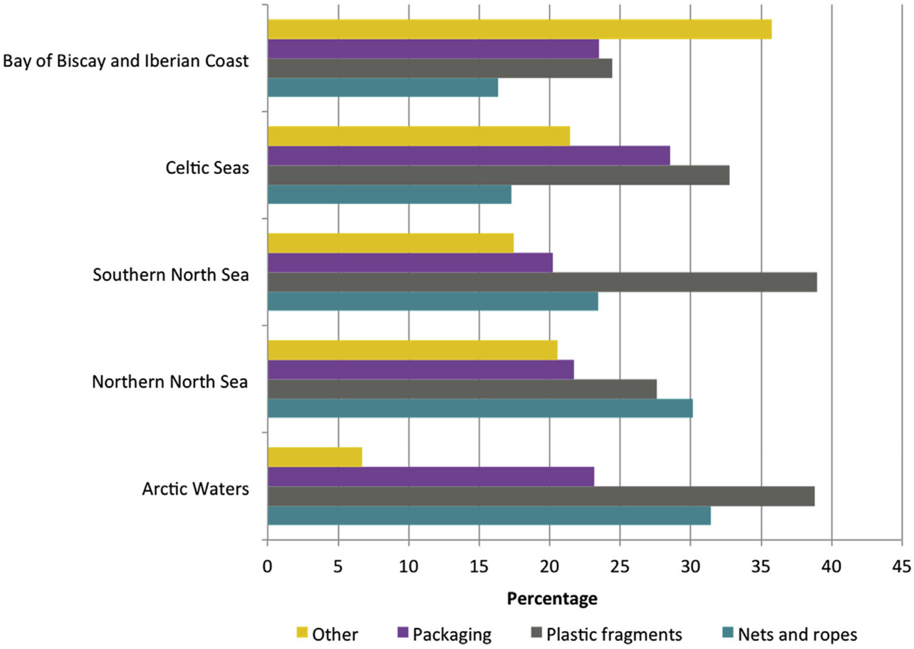

Fig. 2. Composition of marine litter in 2014/15 in the OSPAR Maritime Area (source: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/marine-litter/beach-litter/).

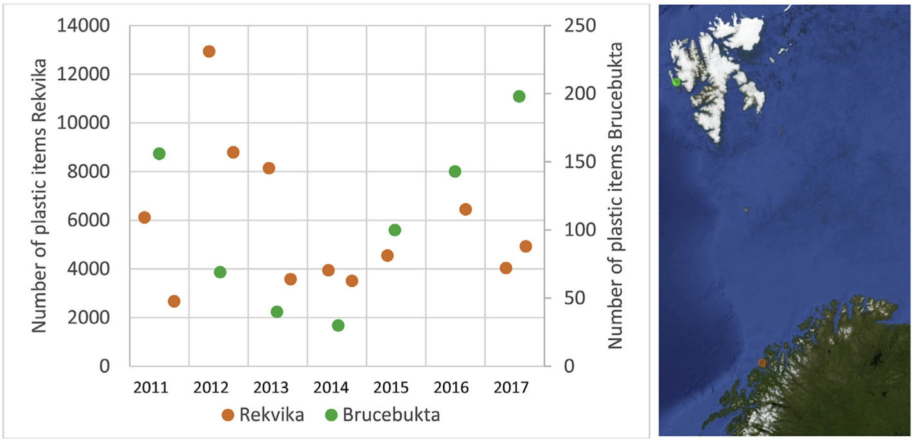

Fig. 3. Average number of plastic litter pieces collected on stretches of 100 m beach at two OSPAR beach monitoring sites in the Norwegian Arctic (Left y-axis: Brucebukta, Svalbard, right y-axis: Rekvika, Norwegian mainland); (data exported from http://www.mcsuk.org/ospar/survey/export).

Pacific Ocean between California and Alaska, than in the Atlantic between the North Sea and Arctic Canada [65] although this comparison did not include the Svalbard value of 88% birds above 0.1 g EcoQO [67].

In addition to seabirds, other organisms, ranging from plankton [36] to megafauna [65,75], ingest plastics in various sizes and numbers, but field measurements from arctic locations and arctic taxa are still scarce, preventing systematic conclusions about organismal susceptibilities and extrapolation to encounter rates of plastics and field distributions of plastic pollution. Ingestion of microplastics by juvenile polar cod was reported, where 2 individuals out of 72 (2.7%) had ingested microplastics [78], confirming uptake of microplastics in arctic fish species. This is comparable to results for Atlantic cod from the Norwegian shelf, where 3% of fish from nordic fjords had ingested plastics, most of them in the harbour of the city of Bergen (Norway) [79], and slightly lower than results from the North and Baltic Seas [80]. These numbers are significantly lower than reports from the North Pacific Central Gyre, where 35% of planktivorous fish had plastics in their stomachs [81]. One additional study examined 11 different benthic invertebrate species on the shelf of the Bering and Chukchi Seas [73]. Abundances of microplastics in 413 specimens ranged from 0.02 to 0.46 items/g wet weight or 0.04–1.67 items/individual. The highest value was recorded at the northernmost site, implying that sea ice and arctic seawater represent possible hotspots and transport media [82].

4. Environmental trends

In general, considerable data gaps prevent an adequate spatial and temporal trend analysis of plastic distribution in the Arctic to date. Below we report documented spatial and temporal gradients, and provide some expectations based on these observations.

4.1. Spatial trends

The convergence zones of the five subtropical gyres represent global accumulation zones for plastic debris [83]. Based on this pattern, a sixth garbage patch was predicted in the central Barents Sea from a hydrodynamic model, but a concentration gradient for plastic pollution in this region has yet to be confirmed by field sampling [9].

Concentrations of microplastics were about the same in the uppermost surface waters of the northern North Atlantic (between mainland Norway and Svalbard's southwest coast) and in the northeast Atlantic off Ireland [52,53]. Subsurface samples, in contrast, had 4 times higher microplastics concentrations, but were sampled with a different method [52]. If there is a latitudinal gradient in microplastics abundance requires confirmation, but physical oceanography patterns may explain these observations, where microplastics travel with the currents of the Gulf Stream, along the Norwegian coast and further northwards into the Arctic Ocean. The Arctic may act as a sink of plastics, as the debris accumulates in these currents and receives inputs from mainland Europe and Scandinavia, and perhaps from even further afield, until it is deposited in arctic pack ice. In turn, plastic particles entrapped in multi-year sea ice for long periods (decades) may be released into the water column upon ice melt, which is expected to increase with continued climate warming [84], turning the sink into a potential source. Information on the distribution of marine plastics and microplastics for the North Pacific is restricted to subarctic regions and mainly available in the form of data from seabirds seabirds [63,85,86]. For arctic regions, only indirect estimations from seabird ingestion are available [68], but no regional trends were found, probably due to small sample sizes, long retention time of plastics in the intestines and long-range migration from Baja California along the continental shelf and via the subarctic North Pacific into the Arctic Ocean.

At smaller geographical scales, Bergmann et al. (2017) noted that one beach (Reinstrandodden) in the northwest of Spitsbergen had a considerably higher litter load than others in the same region, emphasizing the importance of geographical location and orientation relative to the ocean currents for the deposition of beach litter [49]. Along the north Norwegian coast, litter showed increasing trends towards the coast and in deep-sea canyons [87]. Spatial trends of microplastic abundances were also recorded in deep sea sediments within the HAUSGARTEN observatory at 79°56,28′ N and 79°36,25′N, west of Svalbard, where the highest values of 6594.6 and 6348.3 particles/kg occurred at the northernmost stations, indicating increasing concentrations towards the edge of the marginal ice zone [49].

Bivalves, and in particular the cosmopolitan genus *Mytilus*, have been suggested as monitoring agents, as they take up microplastics via filter-feeding, and thus integrate microplastics concentrations in the water column [35]. Due to their wide geographical distribution and common occurrence, they are well suited to provide data across large geographical areas with a standardized method, which is under development. In the Arctic, however, *Mytilus* is at the very margin of its latitudinal distribution, and alternative bivalve or equivalent species need to be identified to also cover arctic regions with comparable data.

4.2. Temporal trends

Only few data are available on temporal trends of marine plastic in the Arctic. Rising sea levels, altered rainfall, changes in solar radiation, wind speed, waves, and oceanic currents associated with climate change are all likely to increase the transfer of debris from coastal cities into marine and coastal habitats including Arctic regions [88]. Only very few studies have investigated temporal trends of marine litter in general and even fewer for arctic regions, and available timeseries, such as the data from bird stomachs so far span years rather than decades [67,68] and the methods applied present challenges, e.g. variable availability of beached birds, their mobility/variations in flight tracks and other factors influencing the variability of amount and type of plastic they ingest (see above). Unfortunately, methods of defining debris (e.g. size classes), sampling and analysis methods vary considerably among studies, limiting our ability to draw conclusions on temporal trends in the Arctic. Below we summarize a few examples of recurring samplings in the same areas in two different arctic habitats: beaches and the seafloor.

4.2.1. Beaches

Plastic litter on beaches varies greatly with season and between years, making them poor indicators for temporal trends. However, beach cleanings are relatively easy to conduct and popular in the general population, and thus represent valuable data sets in the absence of better data sources [61]. As discussed above, two beaches in arctic Norway have been monitored since 2011 (Fig. 3), where the amount of beach litter at the west coast of Spitsbergen (Brucebukta) has increased linearly since 2014 after a decline from 2011 to 2014. Litter on the Norwegian mainland, in contrast, showed a stable number of items since 2014, after a peak in 2012. In how far these data represent long-term trends is, however, difficult to determine. Beaches represent very dynamic habitats where both plastic deposition and removal take place, subject to tides, storms and geographical orientation of the beach in relation to e.g. currents and wind directions. Longer time series are required to elucidate temporal patterns.

4.2.2. Seafloor

Composition and abundance of benthic marine debris were investigated during three bottom trawl surveys in inlet and offshore locations surrounding Kodiak Island, Alaska, 1994–1996 [89]. Surveys consisted of benthic tows of approximately 1.85 km long. The number of collected items varied only slightly between the years, with 77, 115 and 74 plastic items for 1994, 1995 and 1996, respectively.

In a later study in Fram Strait, an image time series across a bathymetric gradient was conducted between 2002 and 2011. Photographs taken at a set camera transect were analysed in 5 years (2002, 2004, 2007, 2008 and 2011) to assess the quality and quantity of litter in the deep sea at 2500 m depth [90]. A total of 2878 images, equivalent to an area of 8570 km^2, were analysed. While the number of images showing litter decreased from 2002 to 2008, the following 5-year period showed a significant increase of litter, from 0.54% (2008) to 2.87% (2011). Within the monitored time period, the number of litter particles/km^2 varied between about 1000 in 2007 and 7500 in 2011 [90]. In an additional measurement in 2014, a strong increase in marine litter was demonstrated overall for the given decade (2002–2014). The abundance of litter correlated with the number of northbound ships, level of fishing activity and sea ice extent [91].

These studies demonstrate the variability and associated uncertainty of plastic litter abundance measurements in different regions from sampling campaigns representing snapshots in time. International efforts thus work towards standardized monitoring protocols to improve the data base for spatial and temporal plastic litter trends [21].

5. Impacts on biota

Plastic has been known to cause harm to iconic wildlife for decades, but also the more inconspicuous fauna of lower trophic levels is affected, especially by micro- and probably nanoplastics, but these interactions are less obvious and more difficult to study. A number of effects include either mechanical interactions such as entanglement, ingestion, blockage of intestines and/or hindering limb movements [92], or toxicological effects of harmful plastic-related chemicals [93]. The entire food web is concerned, from small plankton to top predators such as seals, whales and polar bears, but also terrestrial animals such as reindeer [54,94–100]. However, the complex interactions of physico-chemical and biological processes contributing to impacts are insufficiently understood (Fig. 4).

Plastics can be ingested accidently, or because they resemble food items. Many marine organisms are filter-feeders, where microplastics overlap in size range with prey and selection against inert particles is little developed [32] and hampered by nutritious biofilms [36]. The only quantification of microplastic in zooplankton was conducted in the region off Vancouver Island (northeast Pacific), reporting encounter rates of 1 particle per 34 copepods and 1 per 17 euphausiids [54,55]. These taxa are essential and highly abundant food web components at the base of the less diverse Arctic trophic chains and thus an important group to study. They represent a high potential for transferring plastics up the food chain through biomagnification or enhance vertical flux of microplastics in faecal material [34], but studies from arctic representatives such as *Calanus* spp. or *Metridia* spp. are to date absent.

Although reports for polar species are still rare, first evidence is beginning to emerge for larger organisms, e.g. for fish [51,75], and invertebrates [101]. The consequences of plastic ingestion for health and fitness parameters such as growth, survival, performance and reproduction are, however, largely unknown for arctic species, although a number of studies have recently investigated such effects [102,103] with relevance also for Arctic species. While some organisms simply egest plastic particles upon passage through the intestines [32,33,104,105], particles of plastic may be retained in the digestive system causing a decrease in feelings of hunger and subsequent reduced intake of food [106]. As an example for seabirds, Cape petrels need about 2 months to excrete 90% of the ingested plastic when they return from polluted northern wintering areas to their pristine Antarctic breeding area [73]. Plastic particles can also be transferred to offspring in seabirds, if they are fed by regurgitation [107]. Finally, plastic ingestion can occur as a result of consumption of plastic-contaminated food items. As a direct consequence of ingested plastic, pollutants can be released and transferred from ingested plastic into the organism's tissues, causing potential toxicological effects. How these deleterious effects impact arctic biota in particular, has not been studied so far, but their fat-rich tissues may make them particularly prone to toxicological effects from lipohilic contaminants in plastic.

Macro- and microplastics are bioavailable to many organisms ranging from plankton to whales, and may bioaccumulate within individual organisms over time and/or be transferred up the food chain (biomagnification). Also, direct uptake by high trophic level organisms, such as seabirds and marine mammals, has been observed (see 2.6). This direct uptake adds to the plastic load of the organism with simultaneous uptake and potential internal release of a variety of chemicals [108]. Plastic is generally able to carry a broad range of toxic chemicals to all parts of the Arctic environment, increasing exposure risk for ingesting organisms. Arctic biota exposed to plastic pollution may be especially vulnerable to contamination from ingested plastic, as they are already under environmental stress from climate warming, pollution, and ocean acidification. Relatively minor toxicological effects may impact more severely on their fitness than in temperate regions. On the other hand, plastic may act as a passive sampler and have a cleansing effect if contaminant concentrations in food or the surrounding environment are higher than in the ingested plastic [109]. But fugacity and concentrations of the respective chemical in the surrounding environment are important to consider, and plastics may play a variable role in increasing or decreasing chemical exposure post-ingestion [77,110]. Bioaccumulation of microplastics and associated contaminants into an arctic food web was simulated in a theoretical model [111]. In this study, microplastics ingestion decreased PCB uptake, because PCBs biomagnify more readily via

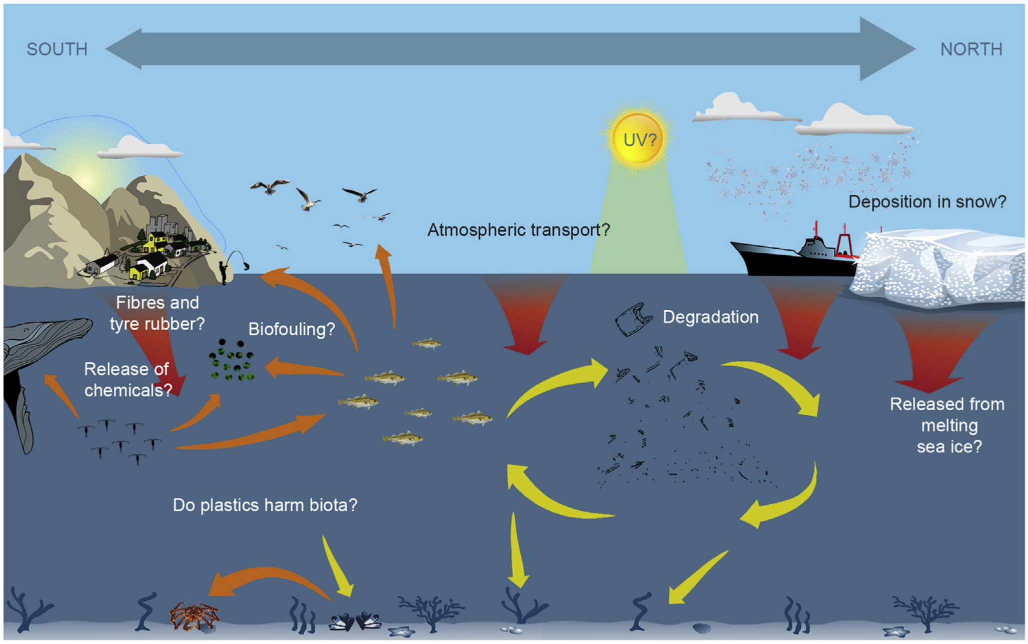

Fig. 4. Examples for knowledge gaps of the distribution, transport, and impact of plastic litter in Arctic systems. Red arrows = plastic litter input, yellow arrows = transport pathways, orange arrows = food web transfer.

regular food than from plastic. PAHs, however, seem to show the opposite behaviour. They biomagnify more with increasing microplastic ingestion, since the fraction of PAHs available for metabolization decreases when bound to the plastic, adding another layer of complexity to the study of impacts of plastic pollution on biota.

6. Conclusions

The body of literature presently available on plastic pollution in the Arctic demonstrates that this emerging contaminant presents a problem also in this remote region. Although reports are scattered across an immense geographic area and use different methods, it is clear that plastics are ubiquitous in arctic environments, and receive plastic litter from both local and remote input sources, but data coverage to date is insufficient to map these dynamics. The few data show that the Arctic is not significantly less polluted with plastic litter than more populated areas further south, but in how far this is a special case for the European Arctic with its large input of water from the Atlantic current needs further investigation. The definitions for debris types and size categories, sampling methods, reported units and modelling approaches to interpret patterns in space and time vary among studies and require harmonization. General conclusions about temporal and spatial trends are not yet possible, but internationally standardized monitoring efforts begin to yield time series data. An optimal monitoring method is, however, still outstanding, as beach cleanings may not reflect true changes due to large variations in weather-dependent depositions and removal of plastic litter. Monitoring in biota such as northern fulmars is equally challenging, and marine benthic invertebrates have been suggested as monitoring species, integrating microplastics pollution in the water column. A suitable arctic species needs to be identified for this purpose. Time series efforts are urgently needed in multiple matrices, not only in oceanic, but also in terrestrial and freshwater systems.

How arctic conditions influence transport, sedimentation, bioavailability and degradation is only poorly understood. The few reports of in situ measurements of plastic particles in arctic and subarctic regions, reports of high amounts of plastics found in arctic seabirds, and experimental evidence that zooplankton at the base of the food chain readily ingest microplastics strongly suggest that biota in the Arctic are at risk and may suffer from negative effects and or biomagnify plastics up the food chain. Considering that macro- and especially microplastics cannot be effectively removed from the Arctic, a better understanding of the degradation processes, biota interactions, bioaccumulation, possible leaching of chemicals and associated toxicological effects is required. Exacerbating environmental changes such as climate change, pollution with other contaminants, ocean acidification etc. may have synergistic or antagonistic effects with plastic litter impacts, and need to be considered in multi-stressor scenarios. Legacy plastic debris entrained in sea ice will be remobilised when sea ice melts, while transport and mixing may increase with less stable weather patterns. Future studies should focus on filling the current knowledge and data gaps, as well as their relevance for risk and impact assessments.

Declaration of competing interest

The authors declare that they have no conflict of interest, including any financial, personal or other relationships with other people or organizations that could inappropriately influence, or be perceived to influence, their work.

Acknowledgements

This review was supported by the Arctic Monitoring and Assessment Program (AMAP) and the Fram Centre Flagship Hazardous Substances. We would like to thank Chris Emblow for revisions of Fig. 4.

References

[1] J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, R. Narayan, K.L. Law, Plastic waste inputs from land into the ocean, Science 347 (6223) (2015) 768–771.

[2] P. Europe, Plastics- the Facts 2017, 2017 (Belgium).

[3] C. Schmidt, T. Krauth, S. Wagner, Export of plastic debris by rivers into the sea, Environ. Sci. Technol. 51 (21) (2017) 12246–12253.

[4] E. van Sebille, M.H. England, G. Froyland, Origin, dynamics and evolution of ocean garbage patches from observed surface drifters, Environ. Res. Lett. 7 (4) (2012).

[5] S. Allen, D. Allen, V.R. Phoenix, G. Le Roux, P.D. Jimenez, A. Simonneau, S. Binet, D. Galop, Atmospheric transport and deposition of microplastics in a remote mountain catchment, Nat. Geosci. 12 (5) (2019) 339–+.

[6] E. van Sebille, C. Wilcox, L. Lebreton, N. Maximenko, B.D. Hardesty, J.A. van Franeker, M. Eriksen, D. Siegel, F. Galgani, K.L. Law, A global inventory of small floating plastic debris, Environ. Res. Lett. 10 (12) (2015).

[7] R.W. Obbard, Microplastics in Polar Regions: the role of long range transport, Curr. Opin. Environ. Sci. Health 1 (2018) 24–29.

[8] T.R. Merrell Jr., Accumulation of plastic litter on beaches of Amchitka Island, Alaska, Mar. Environ. Res. 3 (3) (1980) 171–184.

[9] E. Van Sebille, M.H. England, G. Froyland, Origin, dynamics and evolution of ocean garbage patches from observed surface drifters, Environ. Res. Lett. 7 (4) (2012), 044040.

[10] A. Cózar, E. Martí, C.M. Duarte, J. García-de-Lomas, E. van Sebille, T.J. Ballatore, V.M. Eguíluz, J.I. González-Gordillo, M.L. Pedrotti, F. Echevarría, R. Troublè, X. Irigoien, The Arctic Ocean as a dead end for floating plastics in the north atlantic branch of the thermohaline circulation, Sci. Adv. 3 (4) (2017).

[11] R.W. Obbard, S. Sadri, Y.Q. Wong, A.A. Khitun, I. Baker, R.C. Thompson, Global warming releases microplastic legacy frozen in Arctic Sea ice, Earths Future 2 (6) (2014) 315–320.

[12] I. Peeken, S. Primpke, B. Beyer, J. Gütermann, C. Katlein, T. Krumpen, M. Bergmann, L. Hehemann, G. Gerdts, Arctic sea ice is an important temporal sink and means of transport for microplastic, Nat. Commun. 9 (1) (2018) 1505.

[13] AMAP, Chemicals of Emerging Arctic Concern, Arctic Monitoring and Assessment Programme, AMAP Assessment (2016) 269–275, 2017.

[14] T.S. Galloway, M. Cole, C. Lewis, Interactions of microplastic debris throughout the marine ecosystem, Nat. Ecol. Evol. 1 (2017), 0116.

[15] S. Wagner, T. Hüffer, P. Klöckner, M. Wehrhahn, T. Hofmann, T. Reemtsma, Tire wear particles in the aquatic environment - a review on generation, analysis, occurrence, fate and effects, Water Res. 139 (2018) 83–100.

[16] M. Wagner, C. Scherer, D. Alvarez-Munoz, N. Brennholt, X. Bourrain, S. Buchinger, E. Fries, C. Grosbois, J. Klasmeier, T. Marti, S. Rodriguez-Mozaz, R. Urbatzka, A. Vethaak, M. Winther-Nielsen, G. Reifferscheid, Microplastics in freshwater ecosystems: what we know and what we need to know, Environ. Sci. Eur. 26 (1) (2014) 12.

[17] A.A.D. Machado, W. Kloas, C. Zarfl, S. Hempel, M.C. Rillig, Microplastics as an emerging threat to terrestrial ecosystems, Glob. Chang. Biol. 24 (4) (2018) 1405–1416.

[18] C. Zarfl, M. Matthies, Are marine plastic particles transport vectors for organic pollutants to the Arctic? Mar. Pollut. Bull. 60 (10) (2010) 1810–1814.

[19] L.C.M. Lebreton, S.D. Greer, J.C. Borrero, Numerical modelling of floating debris in the world's oceans, Mar. Pollut. Bull. 64 (3) (2012) 653–661.

[20] D. Lithner, Å. Larsson, G. Dave, Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition, Sci. Total Environ. 409 (18) (2011) 3309–3324.

[21] GESAMP, in: L. International Maritime Organization (Ed.), Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean, 2019.

[22] B.E. Grosvik, T. Prokhorova, E. Eriksen, P. Krivosheya, P.A. Homeland, D. Prozorkevich, Assessment of marine litter in the Barents Sea, a part of the joint Norwegian Russian ecosystem survey, Front. Mar. Sci. 5 (2018).

[23] M. Bergmann, V. Wirzberger, T. Krumpen, C. Lorenz, S. Primpke, M.B. Tekman, G. Gerdts, High quantities of microplastic in arctic deep-sea sediments from the HAUSGARTEN observatory, Environ. Sci. Technol. 51 (19) (2017) 11000–11010.

[24] L.C. Woodall, A. Sanchez-Vidal, M. Canals, G.L.J. Paterson, R. Coppock, V. Sleight, A. Calafat, A.D. Rogers, B.E. Narayanaswamy, R.C. Thompson, The deep sea is a major sink for microplastic debris, R. Soc. Open Sci. 1 (4) (2014).

[25] C.D. Rummel, A. Jahnke, E. Gorokhova, D. Kuhnel, M. Schmitt-Jansen, Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment, Environ. Sci. Technol. Lett. 4 (7) (2017) 258–267.

[26] R. Gunnarsdottir, P.D. Jenssen, P.E. Jensen, A. Villumsen, R. Kallenborn, A review of wastewater handling in the Arctic with special reference to

pharmaceuticals and personal care products (PPCPs) and microbial pollution, Ecol. Eng. 50 (2013) 76–85.
[27] M. Bergmann, M. Klages, Marine Anthropogenic Litter, Springer, 2015.
[28] M. Bergmann, S. Mutzel, S. Primpke, M.B. Tekman, J. Trachsel, G. Gerdts, White and wonderful? Microplastics prevail in snow from the alps to the arctic, Sci. Adv. 5 (8) (2019).
[29] A.D. Bellavin, M.E. Smagorinskii, V.I. Monin, V.A. Chelnokov, Microplastic deformation in powder-metallurgy silumins and its influence on dimensional stability, Met. Sci. Heat Treat. 29 (3–4) (1987) 283–290.
[30] D.K.A. Barnes, P. Milner, Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean, Mar. Biol. 146 (4) (2005) 815–825.
[31] J.E. Winston, Drift Plastic - an expanding niche for a marine invertebrate, Mar. Pollut. Bull. 13 (10) (1982) 348–351.
[32] M. Cole, P. Lindeque, E. Fileman, C. Halsband, R. Goodhead, J. Moger, T.S. Galloway, Microplastic ingestion by zooplankton, Environ. Sci. Technol. 47 (12) (2013) 6646–6655.
[33] J.F. Provencher, J.C. Vermaire, S. Avery-Gomm, B.M. Braune, M.L. Mallory, Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastics, Sci. Total Environ. 644 (2018) 1477–1484.
[34] M. Cole, P.K. Lindeque, E.S. Fileman, J. Clark, C. Halsband, T.S. Galloway, Microplastics alter the properties and sinking rates of zooplankton faecal pellets, Environ. Sci. Technol. 50 (6) (2016) 3239–3246.
[35] I.L.N. Bråte, R. Hurley, K. Iversen, J. Beyer, K.V. Thomas, C.C. Steindal, N.W. Green, M. Olsen, A. Lusher, Mytilus spp. as sentinels for monitoring microplastic pollution in Norwegian coastal waters: a qualitative and quantitative study, Environ. Pollut. 243 (2018) 383–393.
[36] R.J.E. Vroom, A.A. Koelmans, E. Besseling, C. Halsband, Aging of microplastics promotes their ingestion by marine zooplankton, Environ. Pollut. 231 (Part 1) (2017) 987–996.
[37] C.J. Moore, Synthetic polymers in the marine environment: a rapidly increasing, long-term threat, Environ. Res. 108 (2) (2008) 131–139.
[38] L.M. Rios, C. Moore, P.R. Jones, Persistent organic pollutants carried by Synthetic polymers in the ocean environment, Mar. Pollut. Bull. 54 (8) (2007) 1230–1237.
[39] Y. Mato, T. Isobe, H. Takada, H. Kanehiro, C. Ohtake, T. Kaminuma, Plastic resin pellets as a transport medium for toxic chemicals in the marine environment, Environ. Sci. Technol. 35 (2) (2001) 318–324.
[40] A. Bakir, S.J. Rowland, R.C. Thompson, Competitive sorption of persistent organic pollutants onto microplastics in the marine environment, Mar. Pollut. Bull. 64 (12) (2012) 2782–2789.
[41] C.M. Rochman, Plastics and priority pollutants: a multiple stressor in aquatic habitats, Environ. Sci. Technol. 47 (6) (2013) 2439–2440.
[42] E.L. Teuten, J.M. Saquing, D.R.U. Knappe, M.A. Barlaz, S. Jonsson, A. BjÃrn, S.J. Rowland, R.C. Thompson, T.S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P.H. Viet, T.S. Tana, M. Prudente, R. Boonyatumanond, M.P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha, H. Takada, Transport and release of chemicals from plastics to the environment and to wildlife, Philos. Trans. R. Soc. Biol. Sci. 364 (1526) (2009) 2027–2045.
[43] R. Dris, J. Gasperi, V. Rocher, M. Saad, N. Renault, B. Tassin, Microplastic contamination in an urban area: a case study in Greater Paris, Environ. Chem. 12 (5) (2015) 592–599.
[44] L.Q. Cai, J.D. Wang, J.P. Peng, Z. Tan, Z.W. Zhan, X.L. Tan, Q.Q. Chen, Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence, Environ. Sci. Pollut. Control Ser. 24 (32) (2017) 24928–24935.
[45] A.A. Horton, S.J. Dixon, Microplastics: an Introduction to Environmental Transport Processes, Wiley Interdisciplinary Reviews: Water, 2017, pp. e1268–n/a.
[46] D. Eerkes-Medrano, R. Thompson, Chapter 4 - occurrence, fate, and effect of microplastics in freshwater systems A2, in: Eddy Y. Zeng (Ed.), Microplastic Contamination in Aquatic Environments, Elsevier, 2018, pp. 95–132.
[47] D. Eerkes-Medrano, R.C. Thompson, D.C. Aldridge, Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs, Water Res. 75 (2015) 63–82.
[48] P.L. Corcoran, Benthic plastic debris in marine and fresh water environments, Environ. Sci.: Process. Impacts 17 (8) (2015) 1363–1369.
[49] M. Bergmann, I. Peeken, B. Beyer, T. Krumpen, S. Primpke, M.B. Tekman, G. Gerdts, Vast quantities of microplastics in arctic sea ice—a prime temporary sink for plastic litter and a medium of transport, in: J. Baztan, et al. (Eds.), Fate and Impact of Microplastics in Marine Ecosystems, Elsevier, 2017, pp. 75–76.
[50] L.D.K. Kanhai, K. Gårdfeldt, O. Lyashevska, M. Hassellöv, R.C. Thompson, I. O'Connor, Microplastics in sub-surface waters of the arctic central basin, Mar. Pollut. Bull. 130 (2018) 8–18.
[51] S. Morgana, L. Ghigliotti, N. Estévez-Calvar, R. Stifanese, A. Wieckzorek, T. Doyle, J.S. Christiansen, M. Faimali, F. Garaventa, Microplastics in the Arctic: a case study with sub-surface water and fish samples off Northeast Greenland, Environ. Pollut. 242 (2018) 1078–1086.
[52] A.L. Lusher, V. Tirelli, I. O'Connor, R. Officer, Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples, Sci. Rep. 5 (2015) 14947.
[53] A.L. Lusher, A. Burke, I. O'Connor, R. Officer, Microplastic pollution in the northeast atlantic ocean: validated and opportunistic sampling, Mar. Pollut. Bull. 88 (1–2) (2014) 325–333.
[54] J.-P. Desforges, M. Galbraith, P. Ross, Ingestion of Microplastics by Zooplankton in the Northeast Pacific Ocean, Archives of Environmental Contamination and Toxicology, 2015, pp. 1–11.
[55] J.P.W. Desforges, M. Galbraith, N. Dangerfield, P.S. Ross, Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean, Mar. Pollut. Bull. 79 (1–2) (2014) 94–99.
[56] C.-L. Wei, G.T. Rowe, C.C. Nunnally, M.K. Wicksten, Anthropogenic "litter" and macrophyte detritus in the deep northern Gulf of Mexico, Mar. Pollut. Bull. 64 (5) (2012) 966–973.
[57] F. Oliveira, P. Monteiro, L. Bentes, N.S. Henriques, R. Aguilar, J.M.S. Gonçalves, Marine litter in the upper São Vicente submarine canyon (SW Portugal): abundance, distribution, composition and fauna interactions, Mar. Pollut. Bull. 97 (1) (2015) 401–407.
[58] J. Mu, L. Qu, F. Jin, S. Zhang, C. Fang, X. Ma, W. Zhang, C. Huo, Y. Cong, J. Wang, Abundance and distribution of microplastics in the surface sediments from the northern Bering and Chukchi Seas, Environ. Pollut. 245 (2018) 122–130.
[59] V. Fischer, N.O. Elsner, N. Brenke, E. Schwabe, A. Brandt, Plastic pollution of the Kuril-Kamchatka Trench area (NW pacific), Deep-Sea Res. Part II Top. Stud. Oceanogr. 111 (2015) 399–405.
[60] OSPAR, OSPAR Pilot Project On Monitoring Marine Beach Litter, 2007.
[61] M. Bergmann, B. Lutz, M.B. Tekman, L. Gutow, Citizen scientists reveal: marine litter pollutes Arctic beaches and affects wild life, Mar. Pollut. Bull. 125 (1) (2017) 535–540.
[62] L. Polasek, J. Bering, H. Kim, P. Neitlich, B. Pister, M. Terwilliger, K. Nicolato, C. Turner, T. Jones, Marine debris in five national parks in Alaska, Mar. Pollut. Bull. 117 (1–2) (2017) 371–379.
[63] M.D. Robards, J.F. Piatt, K.D. Wohl, Increasing frequency of plastic particles ingested by seabirds in the subarctic North Pacific, Mar. Pollut. Bull. 30 (2) (1995) 151–157.
[64] T. Byers, A. Smith, M.L. Mallory, Diet of black guillemots and northern fulmars breeding beside a High Arctic polynya, Polar Biol. 33 (4) (2010) 457–467.
[65] J.F. Provencher, A.L. Bond, S. Avery-Gomm, S.B. Borrelle, E.L.B. Rebolledo, S. Hammer, S. Kuhn, J.L. Lavers, M.L. Mallory, A. Trevail, J.A. van Franeker, Quantifying ingested debris in marine megafauna: a review and recommendations for standardization, Anal. Methods 9 (9) (2017) 1454–1469.
[66] M.L. Mallory, Marine plastic debris in northern fulmars from the Canadian high Arctic, Mar. Pollut. Bull. 56 (8) (2008) 1501–1504.
[67] A.M. Trevail, G.W. Gabrielsen, S. Kühn, J.A. Van Franeker, Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (Fulmarus glacialis), Polar Biol. 38 (7) (2015) 975–981.
[68] S. Avery-Gomm, J.F. Provencher, M. Liboiron, F.E. Poon, P.A. Smith, Plastic pollution in the Labrador Sea: an assessment using the seabird northern fulmar Fulmarus glacialis as a biological monitoring species, Mar. Pollut. Bull. 127 (2018) 817–822.
[69] J.F. Provencher, A.J. Gaston, M.L. Mallory, Evidence for increased ingestion of plastics by northern fulmars (Fulmarus glacialis) in the Canadian Arctic, Mar. Pollut. Bull. 58 (7) (2009) 1092–1095.
[70] T. Bond, V. Ferrandiz-Mas, M. Felipe-Sotelo, E. van Sebille, The occurrence and degradation of aquatic plastic litter based on polymer physicochemical properties: a review, Crit. Rev. Environ. Sci. Technol. (2018) 1–38.
[71] S. Kühn, E.L. Bravo Rebolledo, J.A. van Franeker, Deleterious effects of litter on marine life, in: M. Bergmann, L. Gutow, M. Klages (Eds.), Marine Anthropogenic Litter, Springer, Cham., Heidelberg/New York/Dordrecht/London, 2015, pp. 75–116.
[72] J.A. van Franeker, C. Blaize, J. Danielsen, K. Fairclough, J. Gollan, N. Guse, P.-L. Hansen, M. Heubeck, J.-K. Jensen, G. Le Guillou, B. Olsen, K.-O. Olsen, J. Pedersen, E.W.M. Stienen, D.M. Turner, Monitoring plastic ingestion by the northern fulmar Fulmarus glacialis in the North Sea, Environ. Pollut. 159 (10) (2011) 2609–2615.
[73] J.A. van Franeker, K.L. Law, Seabirds, gyres and global trends in plastic pollution, Environ. Pollut. 203 (2015) 89–96.
[74] F.E. Poon, J.F. Provencher, M.L. Mallory, B.M. Braune, P.A. Smith, Levels of ingested debris vary across species in Canadian Arctic seabirds, Mar. Pollut. Bull. 116 (1–2) (2017).
[75] S. Kühn, F.L. Schaafsma, B. van Werven, H. Flores, M. Bergmann, M. Egelkraut-Holtus, M.B. Tekman, J.A. van Franeker, Plastic ingestion by juvenile polar cod (Boreogadus saida) in the Arctic Ocean, Polar Biol. 41 (6) (2018) 1269–1278.
[76] J.M. Blais, L.E. Kimpe, D. McMahon, B.E. Keatley, M.L. Mallory, M.S.V. Douglas, J.P. Smol, Arctic seabirds transport marine-derived contaminants, Science 309 (5733) (2005) 445.
[77] D. Herzke, T. Anker-Nilssen, T.H. Nost, A. Gotsch, S. Christensen-Dalsgaard, M. Langset, K. Fangel, A.A. Koelmans, Negligible impact of ingested microplastics on tissue concentrations of persistent organic pollutants in northern fulmars off coastal Norway, Environ. Sci. Technol. 50 (4) (2016) 1924–1933.
[78] S. Kuhn, F.L. Schaafsma, B. van Werven, H. Flores, M. Bergmann, M. Egelkraut-Holtus, M.B. Tekman, J.A. van Franeker, Plastic ingestion by juvenile polar cod (Boreogadus saida) in the Arctic Ocean, Polar Biol. 41 (6) (2018) 1269–1278.
[79] I.L.N. Bråte, D.P. Eidsvoll, C.C. Steindal, K.V. Thomas, Plastic ingestion by Atlantic cod (Gadus morhua) from the Norwegian coast, Mar. Pollut. Bull. 112 (2016) 6.
[80] C.D. Rummel, M.G.J. Loder, N.F. Fricke, T. Lang, E.M. Griebeler, M. Janke, G. Gerdts, Plastic ingestion by pelagic and demersal fish from the north Sea

and Baltic Sea, Mar. Pollut. Bull. 102 (1) (2016) 134–141.
[81] C.M. Boerger, G.L. Lattin, S.L. Moore, C.J. Moore, Plastic ingestion by planktivorous fishes in the north pacific central gyre, Mar. Pollut. Bull. 60 (12) (2010) 2275–2278.
[82] C. Fang, R. Zheng, Y. Zhang, F. Hong, J. Mu, M. Chen, P. Song, L. Lin, H. Lin, F. Le, J. Bo, Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions, Chemosphere 209 (2018) 298–306.
[83] A. Cozar, F. Echevarria, J.I. Gonzalez-Gordillo, X. Irigoien, B. Ubeda, S. Hernandez-Leon, A.T. Palma, S. Navarro, J. Garcia-de-Lomas, A. Ruiz, M.L. Fernandez-de-Puelles, C.M. Duarte, Plastic debris in the open ocean, Proc. Natl. Acad. Sci. U. S. A 111 (28) (2014) 10239–10244.
[84] R.W. Obbard, S. Sadri, Y.Q. Wong, A.A. Khitun, I. Baker, R.C. Thompson, Global warming releases microplastic legacy frozen in Arctic Sea ice, Earth's Future 2 (6) (2014) 315–320.
[85] M.C. Goldstein, A.J. Titmus, M. Ford, Scales of spatial heterogeneity of plastic marine debris in the northeast Pacific Ocean, PLoS One 8 (11) (2013).
[86] K.L. Law, S.E. Moret-Ferguson, D.S. Goodwin, E.R. Zettler, E. De Force, T. Kukulka, G. Proskurowski, Distribution of surface plastic debris in the eastern Pacific Ocean from an 11-year data set, Environ. Sci. Technol. 48 (9) (2014) 4732–4738.
[87] L. Buhl-Mortensen, P. Buhl-Mortensen, Marine litter in the nordic seas: distribution composition and abundance, Mar. Pollut. Bull. 125 (1) (2017) 260–270.
[88] M.A. Browne, T.S. Galloway, R.C. Thompson, Spatial patterns of plastic debris along estuarine shorelines, Environ. Sci. Technol. 44 (9) (2010) 3404–3409.
[89] N.A. Hess, C.A. Ribic, I. Vining, Benthic marine debris, with an emphasis on fishery-related items, surrounding Kodiak Island, Alaska, 1994–1996, Mar. Pollut. Bull. 38 (10) (1999) 885–890.
[90] M. Bergmann, M. Klages, Increase of litter at the Arctic deep-sea observatory HAUSGARTEN, Mar. Pollut. Bull. 64 (12) (2012) 2734–2741.
[91] M.B. Tekman, T. Krumpen, M. Bergmann, Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory, Deep Sea Res. Oceanogr. Res. Pap. 120 (2017) 88–99.
[92] D.W. Laist, Overview of the biological effects of lost and discarded plastic debris in the marine environment, Mar. Pollut. Bull. 18 (6) (1987) 319–326. Supplement 2.
[93] A.A. Koelmans, E. Besseling, E.M. Foekema, Leaching of plastic additives to marine organisms, Environ. Pollut. 187 (2014) 49–54.
[94] M. Capolupo, S. Franzellitti, P. Valbonesi, C.S. Lanzas, E. Fabbri, Uptake and transcriptional effects of polystyrene microplastics in larval stages of the Mediterranean mussel Mytilus galloprovincialis, Environ. Pollut. 241 (2018) 1038–1047.
[95] A. Collignon, J.-H. Hecq, F. Galgani, P. Voisin, F. Collard, A. Goffart, Neustonic microplastic and zooplankton in the north western mediterranean sea, Mar. Pollut. Bull. 64 (4) (2012) 861–864.
[96] P. Davison, R.G. Asch, Plastic ingestion by mesopelagic fishes in the north pacific subtropical gyre, Mar. Ecol. Prog. Ser. 432 (2011) 173–180.
[97] M.D. English, G.J. Robertson, S. Avery-Gomm, D. Pirie-Hay, S. Roul, P.C. Ryan, S.I. Wilhelm, M.L. Mallory, Plastic and metal ingestion in three species of coastal waterfowl wintering in Atlantic Canada, Mar. Pollut. Bull. 98 (1–2) (2015) 349–353.
[98] M.C. Fossi, D. Coppola, M. Baini, M. Giannetti, C. Guerranti, L. Marsili, C. Panti, E. de Sabata, S. Clò, Large filter feeding marine organisms as indicators of microplastic in the pelagic environment: the case studies of the Mediterranean basking shark (Cetorhinus maximus) and fin whale (Balaenoptera physalus), Mar. Environ. Res. 100 (0) (2014) 17–24.
[99] M.C. Fossi, C. Panti, C. Guerranti, D. Coppola, M. Giannetti, L. Marsili, R. Minutoli, Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera physalus), Mar. Pollut. Bull. 64 (11) (2012) 2374–2379.
[100] K.L. Law, S. Moret-Ferguson, N.A. Maximenko, G. Proskurowski, E.E. Peacock, J. Hafner, C.M. Reddy, Plastic accumulation in the north atlantic subtropical gyre, Science 329 (5996) (2010) 1185–1188.
[101] A.L. Dawson, S. Kawaguchi, C.K. King, K.A. Townsend, R. King, W.M. Huston, S.M. Bengtson Nash, Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill, Nat. Commun. 9 (1) (2018) 1001.
[102] M. Cole, P.K. Lindeque, C. Halsband, T.S. Galloway, Microplastics as contaminants in the marine environment: a review, Mar. Pollut. Bull. 62 (12) (2011) 2588–2597.
[103] S.L. Wright, D. Rowe, R.C. Thompson, T.S. Galloway, Microplastic ingestion decreases energy reserves in marine worms, Curr. Biol. 23 (23) (2013) R1031–R1033.
[104] J. Hämer, L. Gutow, A. Köhler, R. Saborowski, Fate of microplastics in the marine isopod idotea emarginata, Environ. Sci. Technol. 48 (22) (2014) 13451–13458.
[105] K.L. Kaposi, B. Mos, B. Kelaher, S.A. Dworjanyn, Ingestion of microplastic has limited impact on a marine larva, Environ. Sci. Technol. 48 (3) (2013) 1638–1645.
[106] J.A. Ivar do Sul, M.F. Costa, The present and future of microplastic pollution in the marine environment, Environ. Pollut. 185 (2014) 352–364.
[107] T.B. Henry, S.J. Wileman, H. Boran, P. Sutton, Association of Hg2+ with aqueous (C-60)n aggregates facilitates increased bioavailability of Hg2+ in zebrafish (Danio rerio), Environ. Sci. Technol. 47 (17) (2013) 9997–10004.
[108] K. Tanaka, H. Takada, R. Yamashita, K. Mizukawa, M. Fukuwaka, Y. Watanuki, Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics, Mar. Pollut. Bull. 69 (1–2) (2013) 219–222.
[109] A.A. Koelmans, A. Bakir, G.A. Burton, C.R. Janssen, Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies, Environ. Sci. Technol. 50 (7) (2016) 3315–3326.
[110] A.A. Koelmans, A. Bakir, G.A. Burton, C.R. Janssen, Microplastic as a vector for chemicals in the aquatic environment: critical review and model-supported reinterpretation of empirical studies, Environ. Sci. Technol. 50 (7) (2016) 3315–3326.
[111] N.J. Diepens, A.A. Koelmans, Accumulation of plastic debris and associated contaminants in aquatic food webs, Environ. Sci. Technol. 52 (15) (2018) 8510–8520.