Microplastics in Arctic marine ecosystems – sea ice and sediments

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1. Introduction

The Arctic environment is under a profound threat of climate change which has been known for decades. The global temperature rise of 1.5 °C or 2.0 °C from the pre-industrial level will create an extensive loss of sea ice, with severe consequences in and outside of Arctic ecosystems and inhabitants (Screen & Williamson, 2017). However, there is another growing threat to this area which was sometimes considered pristine – that is, microplastics. Plastics have been produced commercially since the 1950s (Geyer et al., 2017), and the first time they were found inside the guts of an organism was from seabirds in the 1960s (Barnes et al., 2009). It is now considered ubiquitous and found essentially in all environments. However, microplastics have been researched very little in the Arctic marine environments up to this date.

Here the amount of plastic and its effects will be covered from the point of incorporation in the sea ice and sediments of the sea floor. Furthermore, I will discuss 1) the mechanism for incorporating microplastics to the sea ice and its temporal stability, 2) the process of microplastics ending up in the seabed and how different sampling methods influence the results, and 3) how microplastics end up in contact with organisms in these habitats and how they affect them. A better knowledge on how much plastics have been found and where will give a better frame for planning how to remove them from natural environments. Additionally, I show how this anthropogenic litter has an exceptional way of travelling long distances to places of little human activities (Barnes et al., 2009).

2. Ocean currents in Polar Areas

2.1 The North Atlantic

Fram Strait and Barents Sea are the main pathways for Atlantic Water to enter the Arctic Ocean, while the Bering Strait contributes only 0.15% of the volume transport up North. The Fram Strait has the most significant role in water exchange in the Arctic Ocean since it is the deepest water passage (Fahrbach et al., 2001). Atlantic Water which flows through the Fram Strait mixes with the water masses from rivers and the Pacific Ocean (Johnsen et al., 2009).

When sea ice forms, the salinity of the water mass increases and makes the water flow back towards the North Atlantic, affecting water masses mostly near Greenland, Iceland and Norway. The West Spitsbergen current has on average water transport of 9.5 Sv (Sverdrup, 1 000 000 cubic meters per second) in a year. The East Greenland Current has an annual average of 13.7 Sv (Johnsen et al., 2009).

2.2 The North Pacific

The ocean current that follows the Bering Strait connects the Bering Sea to the Chukchi Sea, which creates a flow between the North Pacific and Arctic Ocean (Zarfl & Matthies, 2010). The Bering Strait has water transport of 0.8 Sv northwards, mainly because this gateway is only 85 km wide and 50 m deep (Woodgate, 2005). The Bering Strait is divided into two streams, the colder and saltier Anadyr waters in the west, and the eastern Bering Shelf water which is warmer and less saline.

2.3 The Southern Ocean

The Antarctic Ocean encompasses all oceans above 60 degrees south. The main current is the fast-flowing Antarctic Circumpolar Current, which consists of two main fronts (Whitworth & Nowlin, 1987). The median and deep water flows are a single water mass (Circumpolar Deep Water) but the surface can be divided into the two main fronts, the Subantarctic and Polar Fronts. Additional fronts exist in some regions, contributing to the eastward water flow. The Polar Frontal Zone connects the Antarctic and Subantarctic waters.

3. Microplastics as a phenomenon

3.1 Definition of microplastics

Microplastics are plastic particles less than 5 mm in length and they can be divided into two groups: primary and secondary microplastics. Primary microplastics are plastics that have been produced directly to be used. Microplastics are most commonly used in cosmetics, drugs, synthetic clothing and air-blasting media (Andrady, 2011; Auta et al., 2017; Barnes et al., 2009). According to Auta et al. (2017), primary microplastics in commercial use are referred as “open use” as they are meant to be washed away into drains. Secondary microplastics have originated from bigger particles that have fragmented into smaller pieces over time (Auta et al., 2017; Li et al., 2016). Physical, chemical and biological processes contribute to the fragmentation of macroplastics, for example, in the form of photodegradation (Andrady, 2011; Barnes et al., 2009).

The world-wide rate of annual plastic production hit approximately 299 million tonnes in 2013 (Lusher et al., 2015) and by 2015 the production hit 380 million tonnes, making in total 8300 million tonnes since 1950 (Geyer et al., 2017). About 50% of manufactured plastic has been produced between 2002 and 2015 (Geyer et al., 2017). The majority of this material is derived from fossil fuel and, in fact, hardly any of it is biodegradable. For this reason, the only way to abolish plastics is through destructive thermal treatment. Unless destroyed or recycled, debris tends to accumulate in either natural environment or landfills. It has been estimated that 4 to 12 million metric tonnes enter the marine environment annually from land-generated sources (Geyer et al., 2017). Debris has been found in all major ocean basins (Kanhai et al., 2018), and also the contamination of freshwater and terrestrial systems is a growing cause of concern, although not yet studied to a great extent.

Every year 62 000 to 105 000 tonnes of plastic enter the Arctic Ocean (Kanhai et al., 2018; Zarfl & Matthies, 2010). A sixth garbage patch is growing in the Barents Sea region within the next 50 years (Van Sebille, England, & Froyland, 2012). Also, it has been noticed that increased fishing and shipping activities correlate with plastics present (Andrady, 2011; Geilfus et al., 2019).

3.2 Most common types of produced plastic

When only nonfiber plastics are considered, the main groups produced are high and low-density polyethylene (PE, 36 %), polypropylene (PP, 21 %), and polyvinylchloride (PVC, 12 %). Polyethylene terephthalate (PET), polyurethane (PUR) and polystyrene (PS) contribute by less than 10 per cent each. Polyester and the six other groups mentioned contribute 92% of all plastics ever made. Of this, 42 per cent have been used for packaging and 19% for construction industry (Geyer et al., 2017).

3.3 Waste management

Most of the plastic materials that are utilized for packaging stop being used the same year as they have been produced, as regards of material produced from raw materials (Geyer et al., 2017). On the contrary, plastics used for the construction industry stay on use for decades. Geyer et al. (2017) found that by 2015, a total of 5800 metric tonnes of plastic waste had been produced.

There are three ways to handle plastic debris. First, it can be recycled, but this only postpones the final discarding of the material due to several reasons. Most importantly, when different types of polymers mix and get contaminated, the economic value and technical ability to reuse plastic are compromised. Recycling plastic is quite new, and the rate of it is still globally low: 9 per cent (600 tonnes) of all plastic waste has been recycled. Geyer et al. (2017) found that the highest recycling rates are in Europe (30%) and China (25%), but in the United States the rate is only at 9%. Second, this waste can be incinerated, which holds true for 12% of the wastes (800 tonnes). Further, the energy produced could be utilized for example as fuel. However, it is not actively exploited although the technology does exist. Third, and the most common option, is to remove it to managed landfills, open dumps or discard it in the natural environment. Over 60% of plastic waste is either in landfills or accumulating in nature.

3.4 Fragmentation

Estimates of plastic particle longevity range from hundreds to thousands of years, yet is hard to estimate because plastic as a material has existed for less than a hundred years (Barnes et al., 2009; Geyer et al., 2017). The types of fragments and polymers identified are commonly used in everyday life and as industrial items (Andrady, 2011; Barnes et al., 2009). Moreover, debris is being discarded to sea from ships and vessels, some of it purposely. Some of the microplastic particles found in marine environments are microscopic from the start and larger items get fragmented for several reasons. Degradation of plastic particles is a chemical change that results in lowered molecular weight of the polymer and leads to a weaker structure of the material (Andrady, 2011). A polymer can undergo mineralization when all the organic carbon has been converted to CO_2, and this happens only once the fragment has degraded very extensively.

There are four natural ways to degrade plastic materials (Andrady, 2011). Biodegradation is the act of decomposition carried out by micro-organisms. However, micro-organisms capable of metabolizing polymers are rare in nature and thus the significance of biodegradation is negligible. Another insignificant, but possible, way to fragment polymers is through hydrolysis. Having said that, the main pathways are photodegradation and thermooxidative degradation, of which photodegradation is the most important for colder marine environments. UV-B radiation initiates the photo-oxidative degradation, which means that oxygen-rich functional groups develop in the polymer when the polymer weight has decreased. Because the presence of seawater and biofouling substantially decelerates the process of degradation, the major degrading processes happen before plastic debris ends up in the marine environment (Andrady, 2011).

Nevertheless, the smallest particles (less than 0.8 mg) fragment proportionally faster than larger ones, partly because once the particles are degraded into small pieces (ter Halle et al., 2016), they are often cubic in shape and this makes them roll in the water column. Because of this movement, biofouling does not happen in such an extent as it does for parallelepipeds, for instance. Also, cubic pieces are much more likely to erode in the edges. In contrast, parallelepipeds tend to flow one side up, which makes the top side exposed to UV-radiation and the bottom a suitable surface for biofouling and so they fragment at lower rates.

3.5 Long distance transport of debris

Because of their low density, most plastic debris float on the sea surface for long distances, until they start to sink via algae aggregation, fragmentation, biofouling or other ways. Thermohaline circulation is the main convection of global water masses and it happens due to differences in water density. To simplify, water masses heat up in the Equator and flow to the polar areas, where they cool down and rise to the surface, then float back to the Equator. This circulation is effective in transporting water from temperate to polar areas (Kanhai et al., 2018). Hence, in the polar regions, Fram Strait from the North Atlantic side and Bering Strait from the North Pacific side are the main pathways for debris to enter the Arctic Ocean.

4. Location of microplastics

4.1 Microplastics in sea ice

4.1.1 Sea ice formation

When sea ice starts to grow, it begins to form less saline ice crystals from salty seawater (Obbard et al., 2014). These crystals, called frazil, gather and scavenge particles from the water column as ice grows, and it grows from surface to the bottom. Scavenged particles are irregularly shaped and less dense than water, which makes them easy to be incorporated in ice.

4.1.2 Quantity and quality of microplastics in the Arctic sea ice

Arctic Sea ice has been studied very little so far in regard of plastic (but see Obbard et al. (2014) and Peeken et al. (2018)). Obbard et al. (2014) used four different ice cores. All the samples collected contained plastic particles, ranging from 38 to 234 pieces per cubic meter. They found polyester, polyamide, polypropylene, and polystyrene acrylic and polyethylene plastics. Peeken et al. (2018) had five sampling sites and they found 17 different polymer types, largest groups including polyethylene, varnish, polyester, polypropylene, polyamide and ethylene vinyl acetate. Their values were significantly higher than those of Obbard et al. (2014), the highest one being 17 000 particles per liter (17 million per cubic meter) and the lowest 33 per liter (33 000 per cubic meter). This more recent study showed that 67 per cent of microplastics are within the smallest detectable size range (Peeken et al., 2018).

Polyethylene is one of the most important types of polymers economically and it dominated four out of the five ice cores (Peeken et al., 2018). Additionally, polyamide which is usually linked to fishing industry was one of the main particle groups. Ethylene vinyl acetate is used in cigarette filters, and a substantial number of it was found in two of the ice cores.

The water masses from the Pacific flow through the Bering and Chukchi shelves and mix with the East Siberian Sea, and finally discharge into the Atlantic (Jones, 2001). Although the water flow from the Pacific into the Arctic is minor compared to the Atlantic water input, the microplastic particles found in the Arctic Sea ice are likely from the Pacific because the Atlantic water is substantially more saline and warmer, which makes it denser and so it sinks once it meets the colder and less saline water masses coming through the Arctic (Obbard et al., 2014). Because sea ice forms from less saline water, the water mass is likely originates from the Pacific Ocean (Obbard et al., 2014). Sea ice can be considered a temporary sink for microplastic particles, because microplastic concentrations were extremely high (Peeken et al., 2018), and because the suspended organic carbon levels are two orders of magnitude larger in the sea ice than in the water column (Obbard et al., 2014).

It has been predicted that a sixth sea surface garbage patch will form in the Barents Sea within 50 years (van Sebille et al., 2012). This may be a local source and an ending point for microplastics entering and leaving the sea ice, but also a source for plastics ending up in the sediments.

4.1.3 Effects on sea ice albedo

Geilfus et al. (2019) tested with PVC, PET and PP how microplastic incorporation affects sea ice albedo and ice formation. In their microcosms study, Geilfus et al. (2019) found that 30 to 65 per cent of plastics released in the water were incorporated into the sea ice as it formed. They also found that the maximum number of plastic particles were found in the uppermost layer, down to 1 cm. As the depth increased, microplastics were smaller in size and as sea ice grew, concentrations remained constant. Geilfus et al. (2019) considered that high concentration of large plastic particles could have been due to the mechanism of frazil ice to incorporate impurities, such as sediment, as the sea ice initially forms. Additionally, sea surface tension and low concentration of microplastics in the sea water could contribute to higher number of plastics in the ice surface. Furthermore, although the ice temperature and overall thickness remained the same between microcosms, microplastic in the sea ice alter its growth.

In contrast, the sea ice albedo increased with higher microplastic concentration because the impurities on the surface add to the diffuse reflection of incident light (Geilfus et al., 2019). However, the effect on reflection due to the presence of plastics in considerable mostly during the early stages of ice growth and much less later in the stages of high thickness and size of the ice. This also means that once the ice starts to melt, microplastics may increase the rate of ice melt (Geilfus et al., 2019). Because higher microplastic concentrations are associated with higher salinity, an increase in brine on top of the ice surface could increase albedo. Brine is water highly concentrated with salt. The amount of brine increases on top of the ice surface because impurities add brine channels through the sea ice matrix, and this creates a brine skim on top of the surface (Geilfus et al., 2019).

Geilfus et al. (2019) consider that less impurities are incorporated in sea ice when ice growth is slower. In the natural environment, microplastics are spread more homogenously than in microcosms experiments, resulting to a less concentrated number of plastic particles in the sea ice surface than their study shows. However, due to global warming and the resulting ice melt, the decline of multiyear sea ice means that sea ice will be a major source for microplastic particles released to the ocean (Obbard et al., 2014).

4.2 Microplastics in sediments

4.2.1 Background of sedimentation of plastics

Because sea ice acts as a major temporal sink for microplastics, it also acts as a source for plastic particles entering the sediments. Plastic polymers are quite often buoyant but can sink to the bottom of the ocean if being weighed down by organisms or sediment fouling the particle (Barnes et al., 2009). Plastic has been found on seabeds across all oceans of the Earth. It is clear no place on this planet is out of reach for this type of anthropogenic debris (Kanhai et al., 2018), although the Southern Ocean is still the least contaminated due to long distance from highly populated areas (Reed et al., 2018). Sedimentation means the process of material being deposited as sediment. Generally, debris that has sank to the bottom is trapped in areas with high sedimentation and low water flow rates (Barnes et al., 2009). For this reason, the bottom debris is not evenly distributed across the seabed but has a high variation in abundance. Additionally, the topography of the ocean floor has a substantial effect on debris accumulation. Bays, depressions, channels and rocks or wrecks build up mass more effectively than smoother areas. Large rivers are a significant pathway for plastic debris to enter the sea bed because they generally have a high flow rate and strong bottom currents (Barnes et al., 2009).

The distribution pattern of debris on the seabed follows anthropogenic activities, such as highly populated areas, tourism and fishing industry. Plastic waste from commercial fishing activities contribute to approximately 18% of all debris in the ocean (Andrady, 2011), however in main fishing areas this type of debris may be prevalent, such as 70% in Eastern China (Barnes et al., 2009).

4.2.2 Quantity and quality of microplastics in the Arctic Ocean sediments

Large numbers of plastic debris produced have been lost track of, besides the quantities incinerated and recycled (Bergmann et al., 2017). The leftover parts of the material either ends up in landfills or the natural environment, and it has been estimated that between 4 and 12 million tonnes of plastics vanish into the oceans. Plastic debris is found on the ocean floor across the globe (Barnes et al., 2009), and a study by Bergmann et al. (2017) showed the Arctic area is no exception. They studied the seafloor west of Svalbard ranging from 2500-5000 meters of depth. All sampling sites contained microplastics having an average of 4400 particles per kilogram of sediment and, interestingly, the northernmost stations had the highest number of particles.

Results show the highest number of plastics to date on any ocean floor, but this may be due to differences between sampling. Moreover, Bergmann et al. (2017) found that almost 80% of plastic particles were less than 25 μm in size, indicating that studies using visual inspection are likely overlooking a substantial number of particles and thus result in serious underestimates. Additionally, it has been estimated that some of the microplastics may be incorporated in the seafloor fauna, thus not showing in the final results.

The most likely sources for this Arctic seabed plastic debris are distant, highly populated areas, while some debris comes from local sources (Barnes et al., 2009; Bergmann et al., 2017). The thermohaline circulation is probably the main route for long transport from highly populated coastal areas, especially northern Europe. Local inputs, however, should not be overlooked. Fishing and other shipping activities in the Arctic areas, such as tourism, have increased due to sea ice loss over recent years and this has a direct effect on the amount of marine debris (Bergmann et al., 2017). Commercial fishing activities beyond the 12 nautical mile zones are hard to estimate because these outer areas cannot be tracked by local governments. Fisheries around Barents Sea must drop off their load in Tromsø, Norway but in the future the Port of Longyearbyen will establish new infrastructure for loading off the catch, possibly making it more appealing to grow the fishing industry around these areas.

The highest number of plastics are found up north and Bergmann et al. (2017) believe this could be because sea ice can act as a temporal sink for plastics (Obbard et al., 2014; Peeken et al., 2018) and since the stations studied here are located near the marginal ice zone, ice floes are a possible source for this higher debris accumulation. When sea ice breaks during the summer, the ice floes are transported further south via the Transpolar Drift and they melt as they meet warmer water masses from the Atlantic Ocean, releasing entrained microplastics.

Furthermore, algae can sink plastic particles by aggregating while containing plastics, and transport them vertically to the ocean floor. Finally, smaller particles can sink faster than big pieces of debris because they have a relatively larger surface area and so their buoyancy is lower (Bergmann et al., 2017).

4.2.3 Quantities found in Antarctica

In contrary, Antarctica is far away from substantial anthropogenic activities and for this reason it could be considered a reference point for global plastic pollution. Munari et al. (2017) found 5 to 1705 particles per m^2, while Reed et al., (2018) found less than five particles per 10 ml. The biggest number of particles were found near a sewage water system of a research station, indicating that a local source contributed the most. On average, 700 000 pieces of fibers are released by washing acrylic fabric weighing 6 kg (Napper & Thompson, 2016). Reed et al. (2018) reckon that the numbers they found near the Rothera Research Station should be higher if there was no turbulence, so spreading this material is effective by the ocean currents.

4.2.4 Different sampling methods

It is difficult to compare results from different studies because different studies use different types of sampling methods, due to the lack of standard practices for (micro)plastic sampling (Peeken et al., 2018). Studies could then be compared by just looking whether microplastics are present or absent in the specific sampling location. For example, the studies conducted by Munari et al. (2017) and Reed et al. (2018) have a completely different way to portray the plastic particle quantities found in Antarctica.

This is not only a problem when sampling sediments, but also with sea ice cores. Peeken et al. (2018) pointed out that methods used in their study, for example, imaging Fourier-transform (FITR) (Fourier-transform infrared microscopy), can detect substantially smaller particles than most other studies so far. The smallest detected particle was 11 μm, and it was found that 67 per cent of particles identified were approximately in this size range (Peeken et al., 2018). For example, a study conducted by Obbard et al. (2014) did not include this low size range in their identification methods, thus results are not directly comparable. Human bias introduced by visual selection using regular FITR microscopy resulted in a low number of particles (Obbard et al., 2014), while high values were obtained with imaging FITR which detects really small particles because they are easily overlooked if only visual inspection is used (Peeken et al., 2018).

5. Impacts of microplastics in nature

There are several reasons why microplastic particles are of particular concern (Barnes et al., 2009). Firstly, like macroplastics, they can be ingested by organisms and, in addition to large mammals, they can be ingested by very small organisms at lower trophic levels. Second, body tissues can take up this material from the gut, possibly causing clogging and other kinds of hazards. Plastics can work as vectors for toxins and contaminants into animal tissues (Zarfl & Matthies, 2010), and some of them have been observed to cause carcinogenic and endocrine disrupting effects (Barnes et al., 2009). Some toxins also include persistent organic pollutants (POPs) and could potentially be harmful to organisms if ingested in the form of plastic particles (Zarfl & Matthies, 2010). Furthermore, these materials are extremely difficult to remove from the environment due to the microscopic size and fragmentation of larger pieces.

The general habitats considered above – sea ice and sediments – are discussed here, because a lot of organisms inhabit these locations. Knowing the background levels of plastic pollution in these environments is essential for understanding why microplastics are present in organisms, and to which degree.

5.1 Impacts on organisms

5.1.1 Phytoplankton and algae

Although phytoplankton are not heterotrophic and thus do not consume other organisms to produce energy, they are affected by microscopic plastic debris. Nanoplastic particles are significantly smaller than microplastics (less than 1 µm or 100 nm in size, depending on the source) and two algal groups were detected to have absorbed plastic particles (Bhattacharya et al., 2010). Algal cells are partly constructed of cellulose and, surprisingly, both positively and negatively charged microbeads attracted cellulose despite its anionic surface. Bhattacharya et al. (2010) found a difference in absorption between algal groups due to their size and shape, the larger algae attracting beads easier. The main finding was that microbead absorption lowers photosynthetic rate, by either the shading effect of the polystyrene beads on the photosynthesis centers or by blocking nutrient uptake and oxygen flow. This effect on algae could cause potential direct and indirect threats to other organisms and the climate. Ingestion by higher trophic taxa could cause bioaccumulation and lowered photosynthetic rates, possibly leading to an increase of CO_2 levels in the atmosphere (Bhattacharya et al., 2010).

5.1.2 Zooplankton

Thompson et al. (2004) found plastics in zooplankton already in the 1960s, and by 1990s their abundance had increased over time. Zooplankton are important in the marine environment because they are primary consumers and because some economically important species are meroplanktonic in their juvenile life stage (Cole et al., 2013). Additionally, they have a variety of feeding types, which could affect ingestion. Some zooplankton show signs of size-based selectivity, and some showed life stage-dependent selectivity. Copepods ingest less algae when they have been exposed to microplastic beads, and one species has been observed to accumulate microbeads in their gut for up to 7 days (Cole et al., 2013) before egestion. Prolonged gut-retention times may compromise zooplankton's ability to ingest and digest food. Finally, microplastic particles have been observed to attach to the external parts of zooplankton.

5.1.3 Fish

To go further up in the food web, juvenile polar cods (*Boreogadus saida*) were observed to ingest microscopic fibers from anthropogenic litter, although at low quantities (Kuhn et al., 2018). Arctic cod is a key species in the Arctic food web because it is frequently ingested by organisms at higher trophic levels. This observed ingestion could be from the bottom of ice floes (Obbard et al., 2014), because juvenile polar cods are strongly associated with under-ice habitats and prey on ice-associated amphipods and copepods (Kuhn et al., 2018).

5.1.4 Benthic taxa

Most studies consider shallower waters and deep-sea basins to lack research due to difficulties in sampling, for example. For this reason, little is known about deep-sea organisms, especially in the Polar areas. Oral areas, feeding apparatus, symbiotic zoanthid tentacles, stomach and gill areas were observed to have microfibers in Cnidaria, Crustacea, Echinodermata and

Arthropoda in Atlantic and Indian Seas, near the Equator (Taylor et al., 2016). Not all suspension-feeding organisms contained plastics, but all predatory, deposit and detritivore-feeders had at least some (Taylor et al., 2016). Particles were found in low numbers, but that could be of several reasons. Additionally, prey capture rate and growth rate of some cold-water coral species were observed to be reduced when they were exposed to microplastics (Mouchi et al., 2019). Thompson et al. (2004) tested the potential for the ingestion of microplastics in aquatic invertebrates and found that all the species they tested had ingested plastics within a few days. These organisms included amphipods, lungworms and barnacles, with feeding types of detritivores, deposit feeders and filter feeders.

‘Marine snow’, which includes macroscopic marine organisms, detritus and inorganic matter (Alldredge & Silver, 1988), is important to seafloor organisms because the majority of them are very dependent on this organic detritus supply for energy (Taylor et al., 2016). Because plastic particles are close to the size range of ‘marine snow’, they could pose a potential threat to deep-sea organisms through ingestion.

5.1.5 Sea birds

The first evidence of plastic in the environment was found from seabirds as early as the 1960s (Barnes et al., 2009). Sea birds can erroneously mix plastics for food in the sea surface or ingest them by preying on other organisms which have ingested plastics (Tanaka et al., 2013). Tanaka et al. (2013) found a correlation between the number of plastic particles ingested and toxic chemicals in the body tissues, meaning that plastics are a vector for toxic chemicals.

5.1.6. Marine mammals

For marine mammals, ingesting plastics can lead to blocking the passage of food or reducing the intake of nutrients, resulting in malnutrition, starvation and even death (Lusher et al., 2015). Microplastics have been found in harbor and fur seals, in addition to True’s beaked whales. However, these results are not from the Arctic areas but from much more temperate areas. Nevertheless, considering that microplastics are ubiquitous and lower trophic taxa have been found to ingest plastics in the Arctic areas, it is likely the risk is posed on the Arctic marine mammals, too.

5.1.7 The Antarctic region

Because anthropogenic litter is ubiquitous, even the Antarctic regions are not unaffected by micro- and nanoplastics. Sea urchins, specifically *Sterechinus neumayeri*, are abundant in the

Southern Ocean, and they are sensitive to environmental changes and toxins due to their low metabolic rate and growth (Bergami et al., 2019). Because of their size, nanoplastics can enter animal tissues, including immune cells. In their in vitro experiment, Bergami et al. (2019) found that this Antarctic sea urchin species had polystyrene nanoparticles internalized by phagocytosis and this finally resulted in oxidative stress, inflammatory responses and apoptosis.

5.1.8 Other things to consider

Differences in sampling methods can also be seen in studies considering effects on organisms. For example, microbeads are hard to detect, and some studies, such as Taylor et al. (2016), did not consider them in their study, which could mean the results are not accurate. Also, particles could be transitory in the digestive system and thus not accumulate in stomachs over a long period and some functional feeding types may be more vulnerable to plastics. Furthermore, the study areas may happen to have low density of plastic debris and thus be less likely to be ingested (Taylor et al., 2016), because plastic is not distributed homogenously in the marine environment or seabed (Barnes et al., 2009).

5.2 Impacts on the environment

5.2.1 Greenhouse gases

Because the production of plastic materials is growing, so do the emissions from producing and incinerating it (Center for International Environmental Law (CIEL), 2019). By 2050, the emissions from producing and incinerating is predicted to make up 14% of leftover CO_2 budget, if we were to stay under the +1.5 °C level of global rise in temperature, which means 2.8 billion tonnes of CO_2e. According to CIEL (2019), low-density polyethylene release greenhouse gases, such as methane, ethylene, ethane and propylene, as it fragments in the environment. Additionally, microplastic ingestion and contact with zoo- and phytoplankton may affect the ocean’s ability to act as a carbon sink. Plankton capture carbon dioxide at the surface of the ocean and transport it to the bottom of the ocean as fecal pellets where it is deposited for centuries, but microplastics can cause lowered metabolism, reproductive success and even high mortality in plankton and thus affect their ability to transport, and finally, store carbon. This is of great importance because oceans store approximately 50% of all CO_2 in the world.

Additionally, after being exposed to UV-radiation, plastic material cannot be recycled because the radiation compromises the thermal and structural properties of the material (CIEL, 2019). Hence, debris collected from the ocean can only be incinerated, which increases CO_2 emissions.

5.2.2 Impacts on sea ice

As mentioned earlier, microplastic incorporation into the sea ice affects its albedo and growth (Geilfus et al., 2019). Once the sea ice melts, it can release a substantial amount of debris into the surface and pelagic water column, thus making it available for ingestion for different organisms. Additionally, if albedo is lowered because microplastics make sea ice to melt earlier in the spring, it can have accelerating consequences on the rise of temperature in Polar areas.

5.2.3 Invasive species

Invasive species are a nuisance in the Polar regions. Some invertebrate species have been found to use plastic particles as vectors to migrate great distances to the Arctic and Antarctic regions (Barnes, 2002). There are several types of animal groups that use debris as a ‘mobile home’, such as molluscs, polychaete worms and barnacles, most of which have a cosmopolitan distribution. Shipping allows species to spread around the globe but plastic debris provides a slower way to move, making it easier for animals to survive such trips. Barnes (2002) found that most substantial colonization of debris only occurred up to 60 degrees of latitude, possibly indicating that temperature is the biggest factor preventing species from moving further towards the poles. As the global average temperature continues to rise, many more species may reach the polar regions. The Antarctic has been isolated much longer than the Arctic regions, so the spread of new species will likely have much greater impacts on the ecology of the Southern Ocean because of its endemic species.

6. Conclusions

There are two main pathways for microplastic debris to enter the Arctic Ocean, the Fram and Bering Strait (Johnsen et al., 2009; Zarfl & Matthies, 2010). Over 8000 million tonnes of plastics have been produced, and a major part of it ends up in the natural environment, where it accumulates (Geyer et al., 2017). The Arctic Sea ice acts as a temporal sink to microplastic particles, and despite being far from major anthropogenic activities, it sinks a substantial amount of litter (Peeken et al., 2018). The main size range of microplastics in the sediments was 25 μm, and where sea ice and significant human activities are present, the amount of microplastics increased (Bergmann et al., 2017). Micro- and nanoplastic particles have been found in all trophic levels with severe consequences on the organisms, from phytoplankton and algae to the largest marine mammals (Kanhai et al., 2018).

Because plastic as a material is so cheap and has a wide range of uses, the level of production is still increasing (Geyer et al., 2017). Without a good debris-handling system, billions of tonnes of it may accumulate in the natural environment in the future. Moreover, with the current trends in ice melt, if the rate continues this way and sea ice has the lowest expected values of microplastic content (38 particles per m^3; Obbard et al., 2014), at least one trillion particles could be released into the oceans. Polymers are damaging to the environment because they are such good materials for packaging (Barnes et al., 2009). For this reason, long-time exposure to microplastic debris could potentially pose a threat to biodiversity because some species are affected more than others (Mouchi et al., 2019). Finally, due to its remote location, accumulation rate of debris in the Antarctic Oceans is notably smaller than elsewhere, but is still increasing (Barnes et al., 2009).

Understanding the processes of how and where microplastics accumulate is crucial if we are to stop it from becoming even more of a problem. Recently, it has been found that even humans ingest microplastics in substantial amounts, although its consequences have not been identified yet. For this reason, it will be even more important to follow the increase of microplastics in the environment and find solutions on how to remove them.

6. References

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