Environment International 139 (2020) 105704

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Mitigation strategies to reverse the rising trend of plastics in Polar Regions

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ARTICLE INFO

Handling Editor: Adrian Covaci

Keywords:
Arctic
Antarctic
Polar
Microplastic
Marine debris
Plastic

ABSTRACT

Plastic marine pollution in the Arctic today illustrates the global distribution of plastic waste of all sizes traveling by wind and waves, entering food chains, and presenting challenges to management and mitigation. While currents move plastics from lower latitudes into the Arctic, significant waste is also generated by remote communities, as well as maritime activities, such as shipping, fishing and tourism, which are increasing their activities as seasonal sea ice diminishes. Mitigation strategies may include monitoring programs of plastic waste abundance and distribution, improved waste management in Arctic communities, Extended Producer Responsibility (EPR) to reverse the transport of waste plastics and packaging from remote communities, incentivized gear recovery of abandoned, lost and discarded fishing gear (ALDFG), gear tagging and tracking, and restricting tourism and employing "leave no trace" policies. Here we report how these mitigation strategies are employed in the Arctic to minimize plastic waste impacts, and move Arctic communities toward better materials management and circular economic practices. The evidence of harm from waste plastics exacerbated by the ubiquity of plastic marine pollution in all biomes, and the rapid reporting of ecological and social costs, together suggest that we know enough to act quickly to manage and mitigate plastics from all sources to the Arctic.

1. The source and sink of plastics in the Arctic represent multiple pathways of inputs and outputs

Plastic marine pollution has been recorded on the sea surface since the early 1970s (Carpenter and Smith, 1972), with an increasing global trend in the nearly half century since that time (Ostle et al., 2019). Microplastics are transported from lower latitudes, where floating plastics accumulate and fragment in the subtropical gyres, with surface or sub-surface currents to higher latitudes (Isobe et al., 2017; Obbard et al., 2014). This is a pathway that has moved significant volumes of plastic into Polar Regions, on the sea surface (Sebille et al., 2015), vertical water column and in sediment (Bergmann et al., 2017).

A recent study shows that while transport models of floating plastics indicate global distribution, this is likely a small fraction of the total mass balance of plastic in the ocean as turbulent mixing of surface waters, fragmentation into ever smaller particles, and biofouling move microplastics deeper into the water column where subsurface currents disperse microplastics into sub-polar and Polar Regions (Wichmann et al., 2019). This model of current movement at and below the surface shows that microplastics accumulating in the subtropical gyres are leaking to deeper currents, and at roughly 60 m the so-called "garbage patches" no longer exist (Wichmann et al., 2019).

Plastic waste entering the Arctic and frozen in sea ice represents a major global sink of man-made particulates. Sea ice is also a transport vector as ice moves, such as seasonal migration of sea ice through the Fram Strait into the North Atlantic (Krumpen et al., 2016), where microplastics are released after melting into waters of the North Atlantic, far from the point at which they were initially frozen into ice (Peeken et al., 2018). Today, with a decreasing trend in sea ice cover (Perovich and Richer-Menge, 2009), the melting of old ice results in the release of microplastic, which is exacerbating microplastic abundance as historical concentrations of microplastic join incoming microplastics (Thompson, 2014). This situation is leading to abundance estimates in the Arctic that rival those recorded in the North Pacific Subtropical

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https://doi.org/10.1016/j.envint.2020.105704
Received 10 October 2019; Received in revised form 28 March 2020; Accepted 29 March 2020

Gyre (Obbard et al., 2014).

Plastics arrive in Arctic regions through surface and sub-surface ocean currents throughout the water column, as well as through atmospheric inputs via wind transport, with sediment likely a permanent sink for much of the world's plastics (Cozar et al., 2017). Wind transport of micro and nanoplastics show prevalence in snow from the Alps to the Arctic (Bergmann et al., 2019), with particle abundance in Arctic snow significantly lower (0 to 14.4 $\times$ 10^3 per liter) than European snow (0.19 $\times$ 10^3 to 154 $\times$ 10^3 per liter) but still substantial. Polymer composition varied strongly, but varnish, rubber, polyethylene, and polyamide dominated overall. Most particles were in the smallest size range suggesting that large numbers of particles below the detection limit of 11 μm, highlighting that atmospheric transport and deposition can be a notable pathway yet to be fully understood (Zhang et al., 2019).

During the recent High North18 scientific expedition to the Arctic Ocean led by the Italian Hydrographic Institute in the Arctic Ocean, seven visual observation tracks were conducted by the European Research Institute between July 16–19, 2018 for macrodebris covering 18,366 m north of Svalbard between 80°44′N and 81°39′N and 7°29′E and 18°12′E. A total of 112 items, averaging one item every 150 m (Borgogno et al., 2019) (in and out of the ice) were observed. Macrodebris observed included fishing gear, ropes, buoys, candy wrappers, consumer packaging, container caps, and miscellaneous debris (Fig. 1). Tourism in the Arctic is gaining access to more remote areas as sea ice forms later and melts earlier, and "last chance" tourism is driving visitors to join cruises and pressures tour operators to follow retreating ice and wildlife. Litter from these activities include macroplastic debris in the form of single-use packaging often lost accidentally due to wind, or lost clothing or outdoor equipment, like gloves and lens caps.

2. Ecological and social impacts

Plastic marine pollution in Polar Regions has varied ecological impacts based on the size, shape, abundance, distribution and bioavailability (frozen, buried, adrift) (Bergmann et al., 2017). Biological interaction, either through ingestion or entanglement, provides another important pathway for microplastics. Filter-feeding organisms that take in microplastics, may bind and discharge them as heavy fecal pellets, are a significant removal mechanism (Katija et al., 2017). While population-level impacts are challenging to ascertain, there is substantial evidence of interaction and impact at a global scale among seabirds (Wilcox et al., 2015), turtles (Schuyler et al., 2014), marine mammals (Baulch and Perry, 2014), and many invertebrates and fish (Gall and Thompson, 2015). In the Arctic, plastic waste may transport invasive species, and some documented impacts to wildlife from derelict fishing gear include entanglement by marine mammals, seabirds, polar bears and caribou (Gregory, 2009; Bergmann et al., 2017).

Socioeconomic and cultural impacts occur as plastic waste enters the Arctic through poor waste management, maritime activities and tourism. Simultaneously, reduced sea ice is affecting the livelihoods for people living and working in the Arctic as native communities face challenges to their traditional ways of life, with new opportunities open for shipping, fishing, and natural resource extraction (Meier et al., 2014). These activities can significantly increase litter and present waste management challenges. Regardless of these challenges, enough is known now to employ mitigation strategies to minimize waste leakage from communities, tourism and maritime activities.

2.1. *Is plastic marine pollution a planetary boundary threat?*

As the ecological consequences continuously grow, scientists and policymakers consider the possibility of including plastic pollution as a planetary boundary threat (Villarrubia-Gómez et al., 2018). The planetary boundaries framework (Rockström and Noone, 2009) defines these threats as precautionary boundaries for several anthropogenic impacts, and the thresholds set to avoid shifts in Earth-system functioning (Rockström and Noone, 2009; Steffen et al., 2007) examples

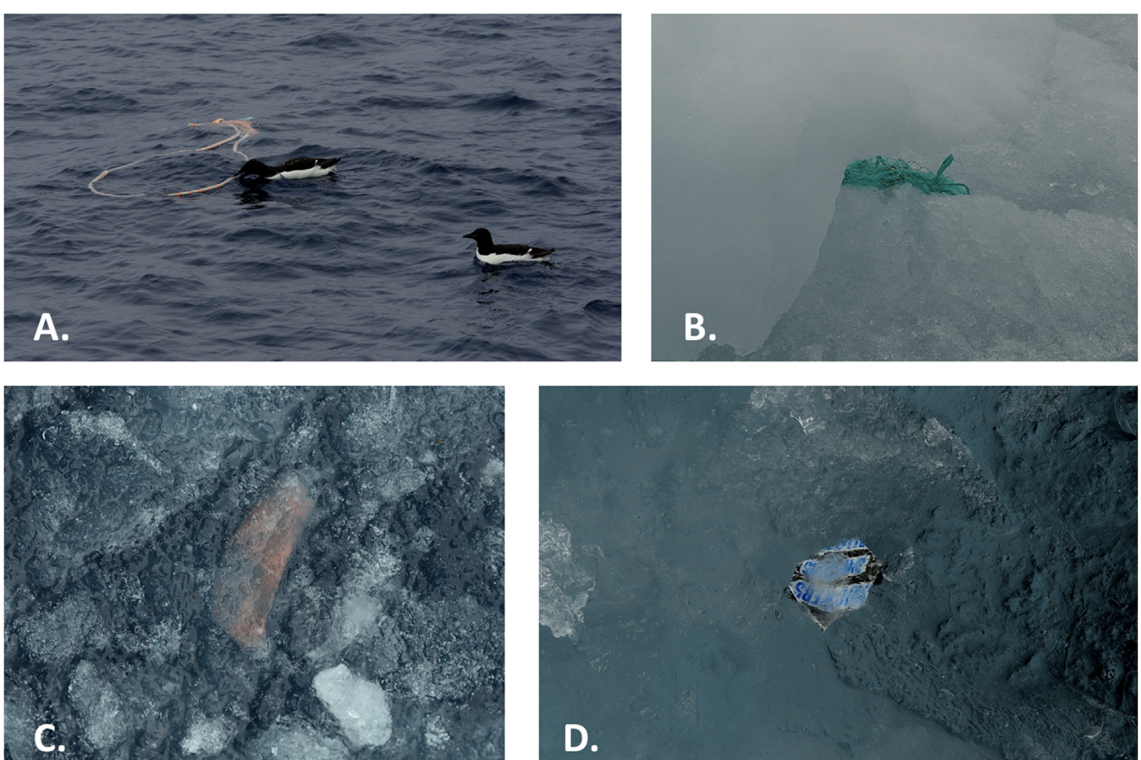

Fig. 1. Photos of macroplastics in sea ice in the region 81°36′N, 18°09′E in the Arctic Ocean taken from the High North 2018 expedition led by the Italian Hydrographic Institute (Borgogno et al., 2019). A. Guillemot pecking at derelict fragment of rope. B. Fishing gear. C. Tube of a consumer product. D. Candy wrapper.

include climate change, ocean acidification and ozone depletion. By providing measurable variables and setting boundaries, the framework demarcates a safe level the globe must operate under in order to avoid more serious deleterious consequences. Plastics flowing into Polar Regions at the surface and below, increased human activity and waste generation, and the release of legacy plastics from melting ice, might be pushing those boundaries.

Chemical pollutants pose a threat at planetary scale when the following three conditions are met (Persson et al., 2013; Macleod et al., 2014): i) the exposure to the pollutant is poorly reversible at a planetary scale; ii) the effects of the pollutant are detectable only when the problem is at a planetary scale; and iii) the pollutant has disruptive effects on earth-system processes. A comprehensive review of marine plastic pollution as a planetary boundary threat (Villarrubia-Gómez et al., 2018) concluded that plastic pollution fulfills two of these three conditions because plastic is ubiquitous in all aquatic ecosystems and its potential removal is unfeasible, particularly micro-and nanoplastic. More research is needed to prove the negative impacts at ecological level and earth-systems processes. However, preliminary evidence shows that plastic could have the ability to intervene in the normal functioning of marine carbon cycles (Cole et al., 2016; Hui et al., 2020), and the fragmentation of marine plastic litter could act as an anthropogenic source of methane emission to the atmosphere (Royer et al., 2018).

Plastic marine pollution exposure is persistent due to non-biodegradability, and it is present in all environments globally, increasingly in Polar Regions. Whether and how the impacts of marine plastic pollution could be affecting Earth-system processes, the third condition of a planetary boundary threat, remains an open question.

3. Measurement, management and monitoring plastic marine pollution

3.1. Measurement and monitoring

A preventative strategy is essential to end the harm of plastics to the Arctic; that is, to substantially reduce the leakage of plastic waste from all sources. Recovery of trillions of anthropogenic particles from water and ice is extremely technically challenging and economically impractical. Improved waste management from within communities and reducing the transport of plastic into Polar Regions will allow the ocean to eject resident floating debris over time (Koelmans et al., 2017), through coastal stranding and the slow sequestration of the smallest particles in deep sea or nearshore sediments.

In recent years, methods to measure plastic emissions to and from all compartments, whether it is flowing through lakes, rivers or oceans, or sequestered in sediments or in marine life, are increasingly being harmonized so that all research is comparable (protocols, units) and comprehensive in that a country or city may measure all plastics in compartments throughout a specific region (GESAMP, 2019). These harmonized research tools, integrated with citizen science, remote sensing technologies, ship-based and in-situ observations, are being proposed to build an integrated marine debris observing system (Maximenko et al., 2019).

Current monitoring efforts to gather baseline data will be integral to evaluating the efficacy of any mitigation. For example, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) employs an extensive monitoring program in Arctic waters of Greenland, Norway and in the Barents Sea to assess beach and seabed litter, and plastics in northern fulmars' stomachs as indicators of plastic waste abundance, distribution and impact (PAME, 2019).

3.2. Managing plastic waste in communities in the Arctic

There are roughly 4 million people who live above the Arctic Circle (Bogoyavlenskiy and Siggner, 2004), consisting of indigenous communities, national territories above the Arctic Circle, and industrial sites where mining, fossil fuel exploration, shipping and fishing activities are centered. Small, highly distributed populations, long transport distances between communities, harsh Arctic climates, competing financial priorities, high cost and lack of resources present inherent challenges in developing environmentally sound waste management practices. As a result, solid waste management services and facilities in Arctic communities vary greatly.

The collection of waste and transport of recyclables in Arctic communities is quite moderate. This is a direct result of high cost of transportation and the fact that there are often no roads or reliable shipping connections to larger cities or distribution hubs where waste can be managed responsibly. As a result, waste continues to accumulate until there is an incentive (driven by economics) for it to be transported to a proper facility. Often, no incentive is presented and communities are left to find an alternative to managing their waste locally.

An emphasis on Extended Producer Responsibility (EPR) to manage plastic used in products and packaging would greatly benefit communities in these scenarios. Often, communities will dispose of their waste into unlined open disposal sites ("dumps") which provide little to no environmental protection. At these sites, macroplastics can easily reenter the environment via wind due to inadequate containment, and microplastics via leachate (Lebreton and Andrady, 2019). This causes significant threat to surface and groundwater. There are some instances where disposal sites are lined – for example, in the City of Iqaluit, in the Canadian Territory Nunavut, there is a thin membrane layer in the landfill for leachate collection. However, the leachate later drains directly into the sea; carrying with it microplastics and other contaminants. Emissions can be substantial, though novel systems that capture microplastics are being introduced to manage these challenges. In Svalbard, a waste management system was constructed that consist of a sediment trap and chemical and biological treatment is removing up to 99% of the microplastics going in from wastewater (Granberg et al., 2019).

In many communities, waste is incinerated. For example, in Greenland, over half of the population incinerates their waste in small-scale incinerators (< 10,000 tonnes year) in communities across the territory (Eisted and Christensen, 2013). Other forms of incineration technology that burn waste to produce energy are typically not feasible in many communities because of their small population size and the associated costs. Instead, waste is often openly burned (especially in remote communities); releasing toxicants to the atmosphere (Fig. 2). It is not always considered feasible to introduce modern technology and waste management practices in Arctic communities. Although, a recent review of waste management practices in communities in Alaska, Canada and Finland, identified strategies (starting from 'no burn' or 'if burn follow some safety instructions until you stop to burn') that integrate new technologies and tools with local needs, and involve inhabitants in remote areas by creating pathways to a sustainable mitigation strategy (Arctic Council and Sustainable Development Working Group, 2019).

The challenges and needs will differ between communities, however the need for financial support and trained waste management personnel is ongoing and can be scaled across the Arctic region.

3.3. Managing fishing industry gear losses and impacts

The majority of ship traffic in the Arctic is from fishing activities, which are increasing as reduced sea ice increases fishing ranges and season (Christiansen et al., 2014). Abandoned, lost and discarded fishing gear (ALDFG) poses a substantial ecological and socioeconomic threat to Polar Regions due to entanglement of marine life, as well as navigational hazards (Gilman, 2015). In 2017, the Arctic Marine Litter project (Arctic Marine Litter Project, 2017) recovered plastic waste from 14 beaches at Svalbard using the OSPAR protocol of measuring 100 m of shoreline at each site, resulting in an average of 48.2 plastic

Fig. 2. Photo showing local landfill burning (photo center) near the community of Pond Inlet (Nunavut territory, Canadian Arctic 72°70′N, 77°95′W) taken while deploying the manta trawl to collect microplastics during the 5 Gyres Institute 2016 expedition to the Canadian Arctic.

items per meter collected, with 80% of items being unidentified fragments, nets and pieces of nets, cap and lids, and strapping bands. Mitigations range from preventative to remedial, including: through innovative fishing practices, to downstream gear recovery of ALDFG (Gilman, 2015).

Preventative strategies may include gear tagging and tracking, alternative materials or technologies that reduce net contact with the seabed, fisheries management and enforcement deter illegal fishing, and simply increasing observers while towing to watch for gear damage or wildlife capture. Conservation goals to manage shipping and fishing activities have been successfully employed to conserve marine mammal populations, like bowhead whales in the North Atlantic, which include strategies such as speed limits and routing changes to decrease vessel strikes, and modification of fishing gear design and deployment practices to reduce entanglement and gear loss (Reeves et al., 2012).

Remedial strategies may include incentives for ADLFG recovery, port facilities to collect and promote gear recovery, sweeping of highly used fishing grounds for lost gear, and less durable and degradable gear. Gear recovery programs, such as “Fishing for Litter”, utilize fishing fleets to retain derelict fishing gear captured during their fishing activities and return it to collection sites in their home harbors. In the two Arctic harbors, Ålesund and Trømso, the Fishing for Litter program recovered 118 metric tons in 2016 and 2017, of which 60% was fisheries related waste (Lofoten et al., 2017).

These initiatives, which can be incorporated into larger international monitoring and management frameworks, aim to move fishing industry materials and practices into a circular economy. Yet in 2015 only 21% of intergovernmental organizations (IGO) mandated in their conventions to monitor and control ALDFG and ghost fishing (Gilman, 2015).

Gilman (2015) identifies five measures explicitly for the purpose of remediating ALDFG and ghost fishing, including banning intentional gear loss, economic incentives to recover gear, port facilities to receive ALDFG, programs that search for derelict gear, and disabling ghost fishing efficiency of ALDFG, yet few IGOs employ these measures. An increase in IGOs setting binding measures to manage ALDFG and ghost gear, and adopt measures to require the use of commercially viable gear technology and methods, would improve the overall Arctic mitigation strategies to reduce harm.

A recent policy brief from the Nordic Council of Ministers (Langedal et al., 2020) identified six key findings aimed to identify areas where Nordic countries could improve management of ALDFG: insufficient reporting of the quantity and location of lost fishing gear; little or no effort on removing lost fishing gear; there exists a significantly greater risk of losing passive fishing gear (e.g. gillnets, pots and fish traps) than active fishing gear (e.g. trawls, purse seines and Danish seines); insufficient awareness-raising initiatives; inconsistent or nonexistent reception solutions for recovered and scrapped fishing gear; insufficient reuse and recycling of fishing gear.

3.4. Managing tourism impacts and litter

Increased tourism in remote Arctic leads to increased impacts as visitors use local services, purchase imported or locally manufactured goods, and introduce or leave waste materials behind (Vaarala, 2006). In many cases, these remote communities lack infrastructure to manage escalating waste and wastewater in the face of thousands of people traveling there (Greenland and Svalbard, i.e.) each year, and as the duration and range of seasonal sea ice diminishes, there is potentially greater access and motivation and perception by tourists to visit the Arctic for “Last Chance Tourism” to witness wildlife before the ecosystem irreversibly changes (Lemelin et al., 2013). Tourism may also pose a biosecurity threat to sensitive areas as cruise ships, their operational equipment and visitors’ personal gear and may be a vector for invasive species (Hall et al., 2010), although entities such as the Association of Arctic Expedition Cruise Operators (AECO) set protocols to minimize biosecurity threats, including a “leave no trace” policy, no natural souvenirs taken, clothing cleaned of soil or seeds, and ships monitor invasive organisms attached to the hull and restrict discharge of ballast water.

A 2013 analysis recognized a lack of an operators management plan, or a central authority to govern the growth of the tourism industry in the Arctic, as well as a lack of guidelines for frequently visited shore locations, other than protected areas (Dawson et al., 2014). One solution to reduce tourism impacts would be for the Arctic states to push for the mandatory application of the Particularly Sensitive Sea Area (PSSA) to the Arctic Marginal Ice Zone (MIZ), the transition region from open ocean to pack ice, which would function to limit and manage tour company operations (Palma et al., 2019). The tour operators themselves have been proactive, establishing in 2003 the Association of Arctic Expedition Cruise Operators (AECO). AECO works with the UN Environment to combat marine plastic pollution, reducing or eliminating the use of single-use plastics on Arctic expedition cruise vessels and involving passengers in cleanups.

3.5. International policy is needed to prevent plastic waste from all inputs

In 2018 the UN Environment Assembly produced an assessment that concluded that current governance strategies and approaches provide a fragmented approach that does not adequately address marine plastic litter and microplastics (UN Environment, 2017), concluding, “Governance must, *inter alia* and in addition to managing what is already in the environment, reduce the risk of plastic becoming marine plastic litter and microplastic by factoring in production forecasts, setting global standards for design, provide security for end-markets and strongly support the 6R approach of reduce, redesign, refuse, reuse, recycle and recover and policy frameworks must be designed to keep pace with innovation, from production to disposal, while providing the necessary environmental guidance."

While broad in scope, there are regional action plans for Polar Regions in effect. The 2017 Fairbanks Declaration of the Arctic Council Ministerial (Fairbanks, Alaska) committed to "assess the scope of the problem and contribute to its prevention and reduction, and also to continue efforts to address growing concerns relating to the increasing levels of microplastics in the Arctic and potential effects on ecosystems and human health" (Arctic Council, 2017). The Arctic Marine Strategic Plan 2015–2025 (AMSP) is a framework to protect Arctic marine and coastal ecosystems, including plastic marine pollution, calling for "improving the understanding of cumulative impacts on marine ecosystems from human activity-induced stressors, including local and long range transported pollution from land and sea-based sources and marine litter (Strategic Action 7.1.3)" (Protection of the Arctic Marine Environment, 2015). While broadly based, this strategic plan outlines what must be done to mitigate marine pollution emissions from communities and maritime activities.

The Regional Action Plan (RAP) on Marine Litter in the Arctic builds upon the Desktop Study on Marine Litter including Micro-plastics in the Arctic (PAME, 2019), with a Phase II objective to develop a Regional Action Plan on Marine Littering both sea and land-based activities, focusing on Arctic-specific marine litter sources and pathways. The flexible structure of RAP allows for periodic updates, as appropriate, and incorporation of new information and priorities as identified by the Arctic Council, and the others. Objectives of RAP Phase II include the development of outreach and communication materials, engagement with indigenous and local communities, and contribute to prevention or reduction of marine litter activities, in order to assist Arctic States in working toward Sustainable Development Goal (SDG) 14, target 14.1: "by 2025, prevent and significantly reduce marine pollution of all kinds."

4. Antarctic challenges compared to the Arctic

Compared to the 4 million people who live above the Arctic Circle, there are 1000–4000 in Antarctica (World Population Review, 2019), winter and summer respectively, therefore community impacts in Antarctica vary widely by region and season. In Antarctica, most settlements are field stations with contained systems of modernized waste management and systems to transport waste to where it can be managed, and in some stations waste recovery is ongoing to mitigate old landfills, metal and hydrocarbon disposal sites, and septic from historical field station activities.

Inputs of plastic marine pollution are primarily from maritime activities and currents transporting waste from the three southern hemisphere ocean basins into the Southern Ocean, and from tourism. Recent studies show abundant microplastics throughout the Southern Ocean and in deep sea sediments (Waller et al., 2017). The Commission for the Convention of Antarctic Marine Living Resources (CCAMLR), established in 1982, researches and makes recommendations to reduce plastic marine pollution impacts, including impacts from plastic ingestion (Rebolledo et al., 2013) and entanglement (Melvin and Sullivan, 2004). Recognizing threats from these inputs, in 2019 the Secretariat of the Antarctic Treaty adopted government recommendations to reduce microplastic emissions from all activities and develop monitoring programs for plastic pollution in Antarctica and the Southern Ocean (Secretariat of the Antarctic Treaty, 2019).

Tourism in Antarctica has risen from less than 1000 tourists annually before 1987 to over 35 thousand per year in 2011, 55,489 in the 2018–2019 season (IATTO, 2020), with impacts ranging from invasive species and wildlife disturbance to sewage disposal and littering (Kariminia et al., 2012). Eight direct and indirect management strategies have been proposed to reduce impacts from Antarctic tourism: quotas on the number of visitors per year, establish off-limits sensitive area zones, service fee to tour operators to finance management, ecotax to support specific management projects, site upkeep with a specific site protection plan, awareness enhancement and public education, ecolabel to certify tour operator materials and practices, and financial incentives to subsidize best management practices (Kariminia et al., 2012). The procedure may be useful for policymakers to provide a reliable view of Antarctic environment sustainability in terms of tourism pressure.

Like the AECO in the Arctic, the International Association of Antarctica Tour Operators (IAATO) primary mission is to conduct environmentally responsible, private-sector travel to Antarctica, and educate passengers in the process. For IAATO members, protection of the environment and adherence to Antarctic Treaty regulations and conventions are mandatory, and tour operators have shown to follow them as a dedicated group, with over 60 operators and another 60 conservation groups, travel and ship agents comprising the association.

5. Conclusions

The abundance and distribution of plastic waste in the Arctic (Cozar et al., 2017; Halsband and Herzke, 2019) warrant employing preventative strategies, as there are too many unknowns and potential for widespread harm to fragile ecosystems. Communities throughout the Arctic are employing novel waste management and new infrastructure to manage waste that can be replicated to significantly reduce local emissions, while maritime activities are establishing best management practices that "leave no trace" as they traverse the region.

What is desired in the Arctic, and globally, is the Circular Economy as a management approach that keeps materials in the system, and thus has been recognized as a successful method for reducing the amount of waste that is produced or mismanaged in a community (Joshi et al., 2019; Walker and Xanthos, 2018). By recycling or reusing products, and thus preventing them from becoming waste, "waste" management becomes "materials" management. Because of a recognition of global plastic pollution, many cities and countries, fishing and shipping fleets, and the tourism industry, are shifting toward materials management strategies to match a more circular economy.

Collectively, these mitigations build a preventative strategy that can minimize impacts from plastic waste and lead to reduced emissions into Polar Regions for the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Financial support throughout this project has been provided by the Baum Foundation to support expeditions, sample collection and analysis (http://thebaumfoundation.org).

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