Polar Record

www.cambridge.org/pol

Managing plastic pollution in the Arctic ocean: An integrated quantitative flux estimate and policy study

Sarah Dewey and Sarah Mackie

Arctic Initiative, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge, MA 02138, USA

Research Article

Cite this article: Dewey S and Mackie S. Managing plastic pollution in the Arctic ocean: An integrated quantitative flux estimate and policy study. *Polar Record* **59**(e36): 1–11. https://doi.org/10.1017/S0032247423000268

Received: 19 December 2022
Revised: 30 September 2023
Accepted: 9 October 2023

Keywords:
policy; oceanography; marine plastic pollution

Corresponding author:
Sarah Dewey; Email: deweys@uw.edu

Abstract

Plastic pollution in the Arctic marine system is sparsely quantified, and few enforceable policies are in place to ameliorate the issue. With an inflow-outflow budget for the Arctic Ocean, we identify gateways through which plastic enters and exits the Arctic marine system. While estimating the flux of plastic through rivers, sea ice, and ocean, we also quantify marine plastic pollution from Arctic shipping and fishing. Plastic fluxes are calculated using horizontal volume fluxes of water and ice and combining them with plastic waste concentration data; flux from fishing and shipping is generated through combining waste estimates with estimated ship traffic. We estimate that fishing and shipping contribute 10^5 tonnes of plastic flux per annum, compared to 10^{-1} tonnes per annum from river inflow. The ocean has a far smaller net outflow, dwarfed by that of ice, at 10^{-8} to 10^{-7} and 10^{-5} to 10^{-3} tonnes per annum, respectively. We examine how a suite of proposed policy interventions would quantitatively change those concentrations, and how the current governance environment makes each feasible; we find interventions targeting vessel traffic most effective. These interventions include a prohibition on the use of certain plastics in fishing as well as a Polar Code permitting scheme.

Introduction

The Arctic, despite being remote, with small numbers of residents and comparatively little shipping and fishing traffic, is not immune to the problem of ocean plastic pollution. Against the region's existing backdrop of dramatic environmental change, plastics have appeared on Arctic beaches (Bergmann et al., 2017); in the ocean and in sea ice (Bergmann et al., 2022); and in the stomachs of seabirds and marine mammals (Amélineau et al., 2016; Bergmann et al., 2022; PAME 2019; van Franeker & Law, 2015).

These plastics pose issues for the environment and the human communities that depend on it. Mortality from entanglement and ingestion decreases food stocks (PAME, 2019; Provencher et al., 2017; Trevail et al., 2015; van Franeker & Law, 2015), and bioaccumulation (Ask et al., 2016; PAME, 2019) harms animal and human health (Barboza et al., 2018; Vethaak & Leslie, 2016). Plastics flowing into the Arctic from other parts of the world can also host invasive species and pathogens, to the detriment of delicate ecosystems (Amaral-Zettler et al., 2020; Barnes, 2002; Barnes & Milner, 2005; PAME, 2019; Wright et al., 2020).

The Arctic Ocean's physical system operates differently in many ways from lower-latitude oceans'. One crucial element of this system is sea ice. As sea ice forms, it concentrates plastic debris (Peeken et al., 2018), so the formation, melt, and movement of sea ice are important to tracking plastic in the Arctic Ocean. Additionally, in other oceans, the majority of marine plastic comes from land-based sources, often transported via rivers (Cózar et al., 2017). However, as this study will show, the sources of plastic in the Arctic Ocean are not primarily land-derived, but instead come from fishing and shipping.

As a result of climate change, the Arctic Ocean sea ice cover is rapidly declining, and therefore it is important to identify plastic pollution sources and circulation today and how these might change in a future Arctic. For example, not only will plastic debris circulate differently in an ice-free Arctic Ocean, but an increase in ship traffic through newly ice-free regions could result in additional plastic input. This manuscript considers marine plastic pollution's behavior in the Arctic Ocean and attempts to anticipate how its occurrence might change in the future, with or without the use of policy tools for mitigation.

Background

This manuscript is the first attempt to unify geophysical budget concepts and regulatory measures that control input and removal of plastic from the Arctic Ocean. As a precedent for physical budgets that include anthropogenic inputs and policy solutions, we can look to the carbon space, in which estimations of emissions reductions are regularly modeled. Because of the diffuse nature of carbon pollution, many of these budgets are global-scale (Lahn, 2020; Rogelj et al., 2016). Likewise, the majority of plastic budgets have been global (Chassignet et al., 2021; Jambeck et al., 2015; Lebreton & Andrady, 2019). Existing regional budgets for the South Korean (Jang et al., 2014) and Scottish (Turrell, 2020) coasts describe fluxes and concentrations of marine debris from natural and anthropogenic processes. Each examination stops short of proposing policy interventions and testing their effect on the budget, which is one aim of this present manuscript.

A critical element of any budget is flux: We can estimate concentrations in a given reservoir using residence times (Kanhai et al., 2018), but have little sense of the stability of the budget—or, in the case of marine plastic pollution, the ability to change the inputs and outputs through policy—without understanding the rates at which concentration changes at the margins of our study area. While plastic concentrations may be higher at the center of ocean gyres, the flux of plastic is greater at the coastlines (Sherman & van Sebille, 2016). Thus, any attempt to change ocean plastic pollution occurrence has a greater impact near the gateways by which plastic can enter or exit the system. With respect to policy, this perspective means that rather than orchestrate open-water cleanups, it is more effective to implement changes near coastlines and for point-source industries such as fisheries and shipping.

The classic budgets of Arctic physical oceanography are those for heat and freshwater. These parameters are tracked because of sea ice's role in the energy balance and Arctic Ocean freshwater's impacts on global circulation. In the case of freshwater, budgets focus on oceanic import and export, sea ice import and export, riverine import, and precipitation import (Aagaard & Carmack, 1989; Serreze et al., 2006).

These budgets suggest how we might track plastic pollution in the Arctic, since it often acts as a tracer of ocean and ice circulation. Here we use "plastic" as a shorthand for plastics under 2.5 cm, which encompasses both meso- and microplastic (GESAMP, 2019). Plastics of these size classes are typically highly buoyant, and tracing surface ocean currents can account for the majority of water-borne plastic (van Sebille et al., 2020), though some amount of microplastic is present throughout all depths in the eastern Arctic Ocean. (Tekman et al., 2020). In the Arctic, marine plastic is typically locally frozen into sea ice, and one floe of ice can accumulate plastic from multiple marine sources over time (Peeken et al., 2018). Parsing these sources is difficult with sparse observations. As well, plastic entrained in ice does not remain so forever; most ice melts within 100 km of its formation site, and approximately one-fifth melts in a different exclusive economic zone (EEZ) from where it is formed. Because of thinning and accelerating ice, exchange of ice across EEZs has increased relative to the 1990s (DeRepentigny et al., 2020; Newton et al., 2017), with implications for regional policy interventions. These factors influence our choice of the full Arctic Basin as a reservoir in this present study.

This manuscript focuses on surface transport of plastics, excluding vertical transport, and so neglects a significant sink of plastic pollution, the seafloor. Fram Strait has a high concentration of plastic in its seafloor sediments (Parga Martínez et al., 2020), especially relative to other Arctic seabeds (Woodall et al., 2014), and this sink is discussed in our analysis. We also do not consider biological transport in this analysis, restricting our calculations instead to physical transport and physical gateways with clear mitigation approaches. We do not include estimates of atmospheric transport of plastics to the Arctic (Bergmann et al., 2019; Evangeliou et al., 2020) or glacially-entrained plastics (Ambrosini et al., 2019), in part because these pathways are still only minimally quantified. We also present simple, back-of-envelope calculations giving potential future ranges for plastic fluxes with different interventions. These calculations admittedly lack the nuance of coupled climate model predictions, but that is not the aim of this present study. Rather, we hope to illustrate the relative contributions of different natural and industrial fluxes, and to examine the policy tools that might have proportionally the most impact on reducing these fluxes.

Current governance environment

The international governance of the Arctic is complex, involving nation States, territorial waters, EEZs, and the Central Arctic Ocean, the last of which is classified as high seas and belongs to no one. Nations are responsible for regulating their own territory, their territorial waters (up to 12 nautical miles from shore) and, in relation to economic activities, their EEZ (up to 200 nautical miles from shore) (UN Convention on the Law of the Sea) and so any response to plastic pollution will ideally be regional in nature but implemented primarily in domestic law a (PAME, 2021) cross multiple countries.

The primary intergovernmental forum within the Arctic is the Arctic Council which was established 1996 to provide an arena for the Arctic nations to negotiate at a ministerial level. Plastic pollution has been a recent focus of the council under the Icelandic chairmanship, and a regional action plan on marine litter was published in May 2021 (PAME, 2021). However, decisions of the Arctic Council are not binding and the organization has no authority to compel compliance with its regional action plan. Because the chairmanship rotates every two years, plastics may or may not be a priority of the Arctic Council in the future. All eight of the Arctic nations are members of the Council, and many other nations with interests in the Arctic have observer status.

Aside from the Arctic Council, there are various international treaties which already seek to regulate pollution within the marine environment, many of which apply to the disposal or release of plastics in the ocean. These treaties include the London Convention and Protocol, the UN Convention on the Law of the Sea, the International Maritime Organization's MARPOL Annex V, and, specifically in the Arctic, the Polar Code. Details of the treaties and their provisions regarding plastic pollution are set out in Table 1.

Despite the existence of these treaties, the flow of plastic into the Arctic Ocean is continuing unabated. Identifying and quantifying plastic entry points to the Arctic in spite of these international treaties enables recommendations which target the source of the problem. Even with this apparent shortfall of the provisions of the current treaties, it is still recommended that these are the ideal platform on which to base any future policies. This is because such treaties provide a basis for legal enforcement, rather than relying on the good-faith effort of signatories to fulfill their commitments. Current efforts, such as the Regional Action Plan recently published by the Arctic Council, are notable in their attempts to seek a reduction in plastic pollution but have no binding authority nor enforcement mechanisms (PAME, 2021).

Another benefit of using the existing treaties as a platform for creating more effective plastic management tools is that these treaties tend to be signed by a large number of nations, not merely the Arctic States. The waters of the Arctic Ocean are used by more

https://doi.org/10.1017/S0032247423000268 Published online by Cambridge University Press

Table 1. Governance tools/fora and applicable sections for addressing marine plastic pollution

Forum	Description	Articles
The UN Convention on the Law of the Sea 1982 (UNCLOS)[29]	The UN Convention on the Law of the Sea 1982 UNCLOS is an international treaty governing all of the world's oceans, including the Arctic Ocean. It has 168 signatories which includes all of the Arctic nations except the USA. It is arguable that UNCLOS is acquiring the status of customary international law (i.e. law which applies to all nations even those who are not signatories.[59]).	• Art 1(4) defines pollution as including substances introduced to the marine environment by man which would (inter alia) harm living resources and marine life, impair sea water quality and reduce amenities. This would cover all forms of plastic in the marine environment. • Art 192 provides a general obligation on states to 'protect and preserve the marine environment'. • Art 194 obliges states to take 'all measures necessary' to prevent the marine environment being polluted. • Art 207 requires states to adopt domestic rules and regulations to 'prevent, reduce and control' pollution, including plastic, from entering the ocean from land-based sources including rivers. • Art 210 encourages the establishment of regional rules, standards and practices to 'prevent, reduce and control' marine pollution.
The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention)[31]	The London Convention is one of the oldest international treaties aimed at protecting the marine environment. It aims to regulate the deliberate dumping of specific, listed substances, including plastic, into the marine environment. It allows permitting for the deliberate dumping of some types of pollution. All of the Arctic states are parties to the treaty.	• Art I requires states, working individually and collectively, to 'promote the effective control of all sources of pollution of the marine environment' as well as to 'take all practicable steps to prevent the pollution of the sea by the dumping of waste'. • Art IV prohibits the deliberate dumping at sea of all materials listed in Annex I. • Annex I includes 'persistent plastics and other persistent synthetic materials'. The types of plastic which may not be dumped at sea specifically include 'netting and ropes'. • For some types of pollution (such as copper, lead and scrap metal, but not plastic), states may issue permits to allow dumping at sea. These permits are issued by a national authority designated by each state.
1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Protocol)[32]	In 1996, a Protocol to the London Convention was agreed with the aim of strengthening the protection of the marine environment. The Protocol reverses the regulatory model of the Convention by prohibiting all deliberate dumping except for permitted materials which are listed in Annex I. Plastic is not listed in the annex so may not be dumped at sea by contracting parties. The aim is that the Protocol will replace the Convention entirely. Most of the Arctic countries are contracting parties but not the United States nor Russia.	• Art 1 commits contracting states to protect the marine environment by taking steps to 'prevent, reduce and where practicable eliminate pollution caused by dumping'. Where possible, measures are to be harmonized. • Art 3 encourages states to adopt a precautionary approach in protecting the marine environment and to introduce measures to make polluters pay. • Art 4 prohibits dumping of all materials listed in Annex 1 and requires permits for dumping other materials. • Art 4 requires states to identify an appropriate authority to issue permits to allow dumping where it is not otherwise prohibited. • Art 7 makes it the responsibility of the state to take measures to punish breaches of the requirements of the treaty.
International Convention for the Prevention of Pollution from Ships (MARPOL) 1973/1978[33]	MARPOL is the main international convention on the prevention of pollution at sea. It was adopted in 1973 under the International Maritime Organisation. MARPOL covers accidental pollution and pollution from operational causes. Annex V has over 150 signatories including all of the Arctic states.	• Annex V covers all forms of garbage disposal in the marine environment. • Includes a complete ban imposed on the disposal into the sea of all forms of plastics. • Applies to all types of vessels, from fishing boats to pleasure yachts. • States are obliged to provide port reception facilities for garbage. • Larger ships must have a plan for the disposal of garbage and a garbage record book should be kept. • States are responsible for enforcement and there is a Member State Audit Scheme. • Annex V, chp 3 makes the environmental provisions of the polar code mandatory.

(*Continued*)

https://doi.org/10.1017/S0032247423000268 Published online by Cambridge University Press

Table 1. (*Continued*)

Forum	Description	Articles
International Code for Ships Operating in Polar Waters 2014 (Polar Code)[34]	The Polar Code is a comprehensive set of rules governing a wide range of issues regarding ships operating in the Arctic and the Antarctic. It was created by the International Maritime Organisation and came into force in 2017. The code is aimed specifically at polar ships, recognizing the realities of the harsh environments encountered at the poles, the remote locations entered into by such ships, the difficulty of mounting a successful rescue mission and the need to protect the regions from pollution and other environmental damage.	• Applies to many types of ship entering the Polar Code areas. • Ships require a Polar Ship certificate, indicating that they are suitable for use in the Arctic or Antarctic. Certificates are issued by Member States. • The discharge of plastics is forbidden. • From 2013, large ships passing through the 'Barents SRS area' have been required to register in either Vardø, Norway or Murmansk, Russia as part of a mandatory ship reporting system. • Member states are encouraged to implement the measures on a voluntary basis for ships not covered by the mandatory code.
Arctic Council Regional Action Plan on Marine Litter, May 2021[30]	The Arctic Council published a regional action plan aimed at reducing the amount of marine litter (primarily plastics) in the Arctic Ocean in May 2021, following a focus by the Icelandic Chairmanship of the Arctic Council 2019–2021.	• Aims to support Arctic States to reduce marine litter, including plastics. • Encourages international cooperation among member states and endeavours to improve communication regarding Arctic plastics. • Demonstrates a non-binding commitment from the member states regarding plastics in the Arctic Ocean. • Identifies the need for harmonized environmental monitoring. • Makes recommendations for actions which could be taken to reduce Arctic plastics.
Voluntary Guidelines on the Marking of Fishing Gear, FAO, 2018[60]	The FAO released a set of voluntary guidelines encouraging the marking of fishing gear. This facilitates the recovery and identification of fishing gear.	• Voluntary Guidelines. • Encourages the marking of fishing gear to identify its origin. • Allows for identification of illegal or irregular fishing. • Allows for the return of fishing gear and increased traceability of gear dumped at sea.

than just the Arctic coastal states and, as the sea ice melts and sea routes and fishing opportunities open up, an increasing number of non-Arctic nations will be exploiting opportunities in the Arctic. A response to plastic in the Arctic Ocean which effectively binds more parties than merely the Arctic states is far more likely to be successful than one which concentrates only on members of the coastal nations or the members of the Arctic Council. A good example of a treaty which works in this way is the Central Arctic Ocean Fisheries Agreement, which came into force in 2021. The agreement was reached under the auspices of UNCLOS and UNCLOS's 1995 Agreement on Highly Migratory Fish Stocks and was signed by the Arctic Coastal States as well as Iceland, China, Japan, South Korea and the European Union.

Methods

In order to quantify the roles of ocean and ice in physically transporting microplastic into and out of the Arctic, we must define a series of gateways similar to those used in seminal freshwater budgets (Aagaard & Carmack, 1989; Carmack, 2000; Serreze et al., 2006). Guided by the work of the Arctic-Subarctic Ocean Fluxes program (Dickson et al., 2008) and the availability of river outflow data, we exclude the Greenland-Iceland-Norwegian Seas from this calculation. Thus, our defined openings to the Arctic Ocean lie at the Bering Strait, the Fram Strait, and the Davis Strait, the last of which captures the majority of Arctic-Atlantic volume exchange in the Canadian Archipelago (Curry et al., 2014) (Fig. 1).

The three principal plastic sources we consider are rivers, ice/ocean fluxes, and shipping/fishing. Errors and decadal projections in each of these estimates are based on stated uncertainties in published data as well as published long-term trends; errors are propagated through these trends. Where there are no robust trends, we assume no trend. We opt to describe annual average plastic fluxes, since the substantial seasonal variations in fishing, shipping, and the hydrologic cycle are challenging to capture.

Rivers

Important at lower latitudes, river runoff (Jambeck et al., 2015) in the Arctic plays a slightly lesser role in plastic input to the ocean. While there is low population density, the watersheds draining into the Arctic Ocean are large, and waste management in many remote Arctic communities is limited relative to lower-latitude cities. To quantify Arctic rivers' contributions to our plastic budget, we apply a global river model to the Arctic. This model estimates the empirical relationship between river plastic output and population density, municipal solid waste (MSW), and river outflow for 40,760 watersheds worldwide (Lebreton et al., 2017).

Here we consider the eight largest Arctic watersheds, which constitute 70% of the pan-Arctic watershed (Holmes et al., 2015): the Yenisey, Lena, Ob, Mackenzie, Yukon, Kolyma, Pechora, and Severnaya Dvina. These data are collected by the Arctic Great Rivers Observatory (Shiklomanov et al., 2021). We also use stated uncertainties (Shiklomanov et al., 2006) and estimated annual trends in discharge (Blunden & Arndt, 2019) to project decadal changes to 2050.

We use these data together with demographic information (Bogoyavlenskiy & Siggner, 2004; Kaza et al., 2018; Larsen &

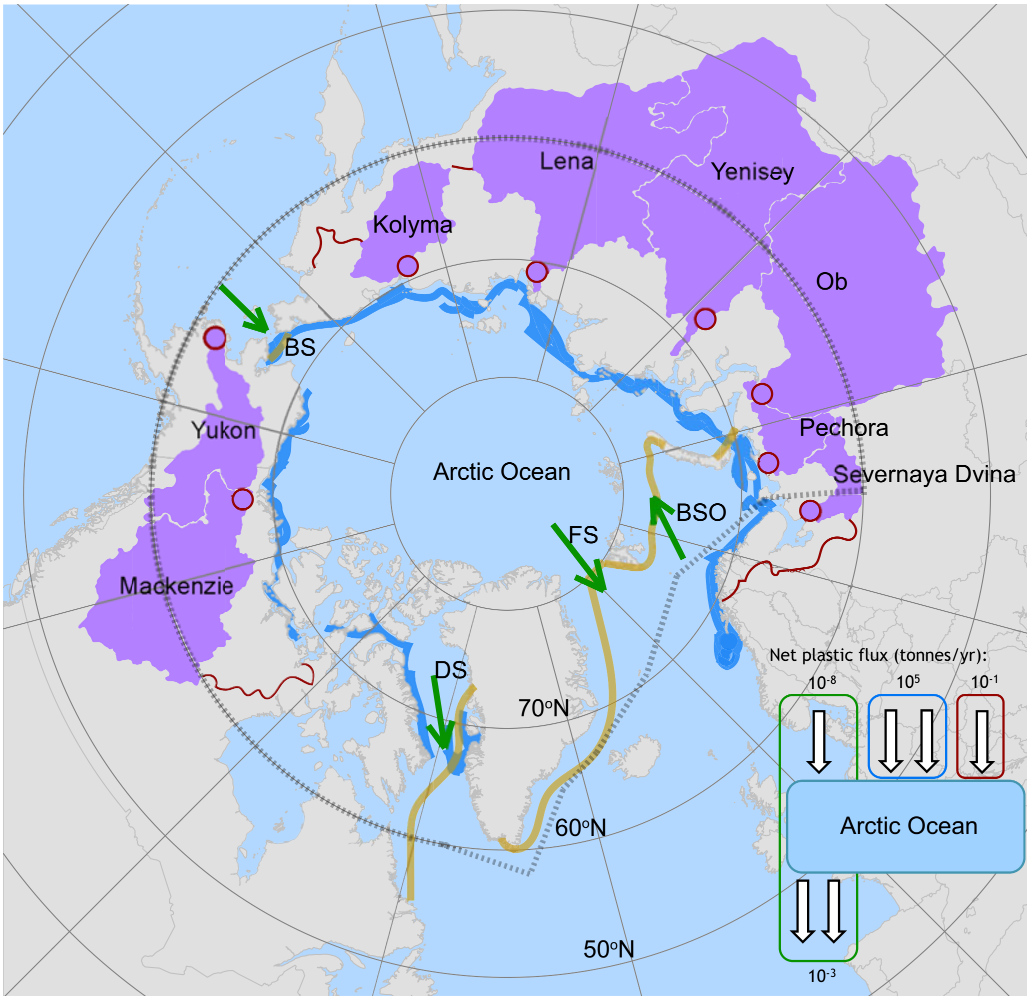

Figure 1. Summary map of study area and order of magnitude flux estimates. The red outline shows the total extent of the Arctic Ocean watershed, and red dots are monitoring stations for each of the eight principal watersheds in purple (Holmes et al., 2015). Plastic flux categories are coded by color: purple are river catchments, green ice/ocean principal flow pathways, and dark blue areas of highest frequency ship traffic (Eguíluz et al., 2016). Gateways are abbreviated as: FS (Fram Strait), DS (Davis Strait), BS (Bering Strait), BSO (Barents Sea Opening). Flux order-of-magnitude estimates are presented in tonnes/year at lower right, with arrows in representing ocean, fishing, shipping, and rivers. Arrows out represent ocean and ice. Shown for reference are the Polar Code area (green) and the median June sea ice extent from 1981 to 2010 (nsidc.org, orange). Basemap generated with Antarctic Mapping Tools for Matlab (Greene et al., 2017).

Fondahl, 2015). Because each river's watershed lies within the USA, Canada, or Russia, we use national demographic data and scale by current watershed population to determine per capita plastic waste generation. Using 2016 adjusted data as well as projections for 2030 and 2050, we estimate the linear trend of decadal changes in watershed population and municipal solid waste generation ($R^2 > 0.97$). While this method does not capture intranational migration, especially in Russia's rapidly urbanizing Arctic (Larsen & Fondahl, 2015), it provides a rough estimate for comparison between riverine and other sources of marine plastic pollution in the Arctic after proposed interventions (Table 2).

Ice & Ocean

To estimate the amount of plastic transported in and out of the Arctic Ocean by ice and liquid seawater movement, we combine flux estimates from four primary gateways—the Fram Strait, the Bering Strait, the Barents Sea Opening, and the Davis Strait—with field-based plastic concentration estimates selected for proximity to each flux gateway. Even with this consideration of sampling location, plastic (especially microplastic) concentration is acknowledged to vary widely within environments, so we present the calculated plastic fluxes as order-of-magnitude estimates (Table 3). The Litterbase tool from the Alfred Wegner Institute (litterbase.awi.de) is used to support this literature review. Cózar et al., 2017 report that the majority of plastics in their collected floating plastic debris range from 0.8 mm to 3.2 mm in length. When field-based plastic concentrations are stated by number, we use a logarithmic formula (Cózar et al., 2014) to convert items per area to mass per area, where the relationship between mass and numerical concentrations for plastic items is $\log(\text{mass}) = 1.21{*}\log(\text{number}) - 3.99$. In the event that plastic distribution is reported by area rather than volume, we use the reported height of collection method (e.g., the height of the Manta trawl net from Lusher et al. [2015]) to convert to volume. In the event of ice concentrations, we use the reported height of ice cores (e.g., Peeken et al., 2018).

The Bering Strait oceanic inflow and Fram Strait ice export are the two fluxes that have statistically significant annual or decadal trends, and so future projections of the other gateways assume zero flux changes; any published uncertainties are propagated from concentration and flux estimates. In order to calculate flux

Table 2. Interventions by pathway

Intervention	Affected Pathways	Potential Projected Changes (tonnes/yr)	Expected Efficacy/Compliance Level	Reduction Scenario
Polar Code permitting scheme	*shipping (per ship), fishing (per ship)*	10^5	high	50%–80%
Tourism beach cleanups	*ocean, ice, rivers*	10^{-1}	low	20%
prohibition of certain plastics	*fishing (per distance)*	10^5	medium	50%
MSW handling	*rivers*	10^{-1}	medium	50%

Table 3. Plastic flux estimates in ice and ocean from multiple sources. Volume fluxes (1 Sv = 10^6 m^3s^{-1}) and trends for each gateway. A sampling of proximal plastic concentrations from field measurements is provided; when field-based plastic concentrations are stated by number, we use a logarithmic formula (Cózar et al., 2014) to convert items per area to mass per area. Sampling method of each study (for example, a 0.16 m-high Manta net by Lusher et al., 2015) is used to convert this quantity to per-volume; plastic flux is then calculated by multiplying the transport rate by this derived mass. Given the patchiness in plastic concentrations, annual plastic flux is presented as an order-of-magnitude estimate. We note that while the size range of plastics in studies may vary, and the majority of studies examined plastics on the scales of micrometers to millimeters, in this manuscript we consider all plastics under 2.5 cm, which encompasses both meso- and microplastic (GESAMP, 2019). Given that plastics of these size classes are typically highly buoyant, this approach serves our study of surface transports; we acknowledge that it may introduce error into our estimates if sampling studies on report plastics of a certain size. Standardization of plastic classification and reporting is necessary for future work in this realm; and indeed the majority of authors listed in the table uniformly define and examine microplastics smaller than 5 mm.

gateway	average annual net transport rate *(positive = into Arctic Ocean)*	trend	sample proximal plastic concentrations *(Nm^{-3})*, and plastic sizes considered	order of magnitude plastic flux *(tonnes/yr)*
Bering Strait	1 ± 0.05 Sv (Woodgate, 2018)	+0.01 Sv/yr (Woodgate, 2018)	0.23 ± 0.07 (Mu et al., 2019); 1.56 mm mean size (most common detected <1 mm)	10^{-10}–10^{-8}
			21.1 ± 5.0 (Ross et al., 2021); fibers O[10^3] × 15 μm	
Davis Strait	−1.6 ± 0.5 Sv (Curry et al., 2014; Østerhus et al., 2019)	–	46.4 ± 62.2 (Kanhai et al., 2018); <5 mm	10^{-7}
Fram Strait (ice)	−2,400 ± 640 km^3yr^{-1} (Spreen et al., 2020)	−54 ± 4 km^3mo^{-1} per decade (Spreen et al., 2020)	4500 NL^{-1}* (Peeken et al., 2018a; Peeken et al., 2018b); <5 mm	10^{-5}–10^{-3}
			108 NL^{-1}* (Peeken et al., 2018b; Obbard et al., 2014); [Obbard <2 mm]	
			*NL-1 here is considered as Nm-3, as the density of melted ice is similar to that of fresh water.	
Fram Strait (ocean)	−1.1 ± 1.2 Sv (Tsubouchi et al., 2018)	–	65.1 ± 9 (Ross et al., 2021)	10^{-8}
Barents Sea Opening	2.3 ± 1.2 Sv (Tsubouchi et al., 2018)	–	0.34 ± 0.31 (Lusher et al., 2015); average 1.93 mm	10^{-10}

estimates, we multiply volumetric ocean and ice fluxes by estimated plastic mass.

Shipping & fishing

We examine fishing and other shipping both by unique vessel traffic and by distance traveled within the Polar Code area, scaling global estimates of plastic pollution from shipping and fishing by the Arctic's relative share of traffic. These two ways of quantifying marine plastic pollution allow us to target interventions per ship or per nautical mile, and to explore hypothetical situations after the expiry of the Central Arctic Ocean fishing moratorium in 2035. We use Arctic Ship Traffic summary data (*PAME – Arctic Shipping Status Report #1*, n.d.) from 2013 to 2019 to estimate long-term trends in plastic waste from shipping and fishing.

Using summary data from PAME's Arctic Ship Traffic Database, (*PAME- Arctic Shipping Status Report #1*, n.d.) we calculate the linear trend in ship numbers and in distance from 2013 to 2019 (distance $R^2 = 0.97$, number $R^2 = 0.60$). Fishing constitutes 45% of distance traveled and 41% of ship numbers. (*PAME- Arctic Shipping Status Report #1*, n.d.) Because the highest-density ship traffic is near to the coasts (Eguíluz et al., 2016), we do not quantify the effect of the Central Arctic Ocean fishing moratorium. As traffic increases in the future and fisheries shift in a changing climate, this omission of the moratorium's effects on our calculations may bear revisiting. To estimate plastic concentrations, we assume a constant value of 1.15 million tonnes per annum globally for fishing, 0.6 million tonnes per annum for other shipping, and 0.016 million tonnes per annum for marine paint (Sherrington, 2016). Since Arctic fishing and shipping are estimated to represent 12.4% and 9.3% of global traffic (Eguíluz et al., 2016), we scale plastic estimates accordingly. We then generate values of plastic pollution "per ship" and "per distance" and use the earlier calculated trends in ship numbers and distance

https://doi.org/10.1017/S0032247423000268 Published online by Cambridge University Press

to estimate plastic pollution from fishing and other shipping to 2050. Uncertainties are calculated for the linear fit and propagated forward in time.

Results

Comparison of calculated plastic fluxes (Fig. 1) shows clearly that fishing and other shipping represent the largest contributors of plastic pollution to the Arctic marine system, contributing an estimated 10^5 tonnes per annum. Ocean import and export are roughly balanced, favoring a slight export through the ocean, though export through sea ice is several orders of magnitude larger than that in the surface ocean, calculated at 10^{-3} tonnes per annum relative to 10^{-8} (Table 3). The magnitude of ice export points to the role that ice might play in "storing" plastic and removing it from the surface ocean through freezing; the substantially smaller amount of ocean and ice transport relative to river and shipping/fishing may be indicative of the role of diffuse sources relative to the "point sources" otherwise considered and of the high variance in ocean and ice plastic concentration field measurements.

Up to 12.7×10^6 tonnes of plastic are estimated to have entered the ocean in 2010 from mismanaged waste worldwide (Jambeck et al., 2015). While the largest estimated annual input to the Arctic Ocean (from fishing; Fig. 3) is an order of magnitude lower, it does not diminish the importance of tackling this pollution problem in such a unique and vulnerable region as the far north.

The estimated plastic fluxes of Jang et al. (2014) and Turrell (2020) into the waters surrounding South Korea and Scotland, respectively, were nearly 10^4 tonnes per annum and 10^2–10^3 tonnes per annum. In each of these cases, riverine input is a major contributor to marine plastic pollution, likely owing in part to the regions' high population density relative to that of the Arctic. We find that riverine plastic pollution entering the Arctic Ocean is on the order of 10^{-1} (Fig. 2), a figure greatly diminished by other direct sources such as shipping and fishing.

Discussion

In order to understand the relative impacts of any proposed policies on each plastic pathway, ice/ocean, riverine, and shipping/fishing, we consider different plastic reduction scenarios: 10%, 20%, and 50% reduction. We later map these scenarios to each intervention.

Riverine plastic pollution poses an interesting challenge: As each river enters the Arctic Ocean, there is an opportunity for a "point source" intervention, such as booms or filtration. However, the changes in river plastic fluxes are smaller than the uncertainty in existing flux estimates (Fig. 2). Additionally, the amount of plastic entering the Arctic Ocean from rivers, on the order of 10^{-1} tonnes/year total, is at least six orders of magnitude lower than that from fishing and shipping (Fig. 3). Ocean and ice gateways are yet smaller by several orders of magnitude, owing in part to their dilute nature. Additionally, difference in the sizes of plastic particles considered by different studies may have contributed to a low bias in ocean and ice flows, dependent on the authors' ability to detect or interest in examining extremely small plastic particles.

Unlike rivers, ice and ocean gateways do not offer easy cleanup solutions, but the flux numbers at these points provide important context for the other numbers considered because of their potential for long-term change and the high concentrations of plastic debris in ice and on the seafloor. Of the ocean gateways, only the Bering Strait ocean gateway has a statistically significant long-term trend (Woodgate, 2018). However, ice export through the Fram Strait is also decreasing decadally (Spreen et al., 2020). The high concentration of deposited seafloor plastics at Fram Strait, with a plastic litter density rivaling that of sea ice (Parga Martínez et al., 2020; Woodall et al., 2014), 813 to 6717 items per km^2 (41% plastic) and O[10^1] items per 50 ml of sediment compared to 108 to 4500 NL^{-1} in sea ice (Peeken et al., 2018; Obbard et al., 2014), suggests that this natural drain is substantial, and so its decline is noteworthy and should be quantified in future work.

The potential changes in shipping plastic pollution fall outside of uncertainty and are larger than rivers. An 80% decrease in fishing plastic results in a flux on the same order of magnitude as shipping under a business-as-usual scenario (Fig. 3). This change suggests that fishing is the area of highest potential impact for plastic pollution reduction efforts; it also underscores the importance of the Central Arctic Ocean fishing moratorium for constraining future pollution projections.

Recommended policy interventions

Following the modelling of where policy interventions could have the most impact, it is possible to come up with a number of recommendations of specific policies which, if adopted, could reduce the level of plastics by the levels identified as necessary to ensure there is no further increase of plastics in the Arctic. The recommendations are outlined here and are quantified below. For the most part, these recommendations are not seeking new treaties – the treaties outlined above already prohibit plastic being thrown into the ocean – but instead are mechanisms by which the various prohibitions on plastic could be implemented or enforced more effectively on a regional level.

Building a regional response using the authority of UNCLOS or the IMO: As the Arctic Ocean is the responsibility of so many different nations, a regional response to plastic pollution is necessary. Instead of relying on the Arctic Council, it would be better for a regional response on plastics to be created under the auspices of Article 210 of UNCLOS or as part of the work of the IMO. A regional response under UNCLOS or the IMO would have far more regulatory strength than the Arctic Council and a dedicated regional response to plastics is more likely to be successful than plastics becoming one of a long list of changing priorities in the Arctic Council. Using UNCLOS or the IMO would avoid difficulties with non-Arctic actors such as China and Japan which only have observer status in the Arctic Council but who are likely to play a large role in future activity within the Arctic area. The USA is not a signatory to UNCLOS but operates within its provisions for matters such as regional fishing management.

Reconciling diffuse vs. point-source pollution: Because the Arctic is fed by enormous river catchments that are sparsely settled, plastic may enter the water at many different points. Thus, one avenue for intervention is to make use of known points of entry. Because sea ports already have a role in compliance with MARPOL-V plastic disposal, they are the obvious place from which the implementation of plastic reduction policies can take place. Making it easier and cheaper for vessels to return to port with their plastic rather than to leave it in the ocean should be a key aim.

Introducing a permitting scheme for ships entering or passing through the Polar Code area: Ships would pay a significant deposit for their permit which would be refunded if either they lost no plastic overboard or, if they did lose plastic overboard, they collected the same weight of plastic from the water as they had lost. Plastic collection points would need to be made available at all

https://doi.org/10.1017/S0032247423000268 Published online by Cambridge University Press

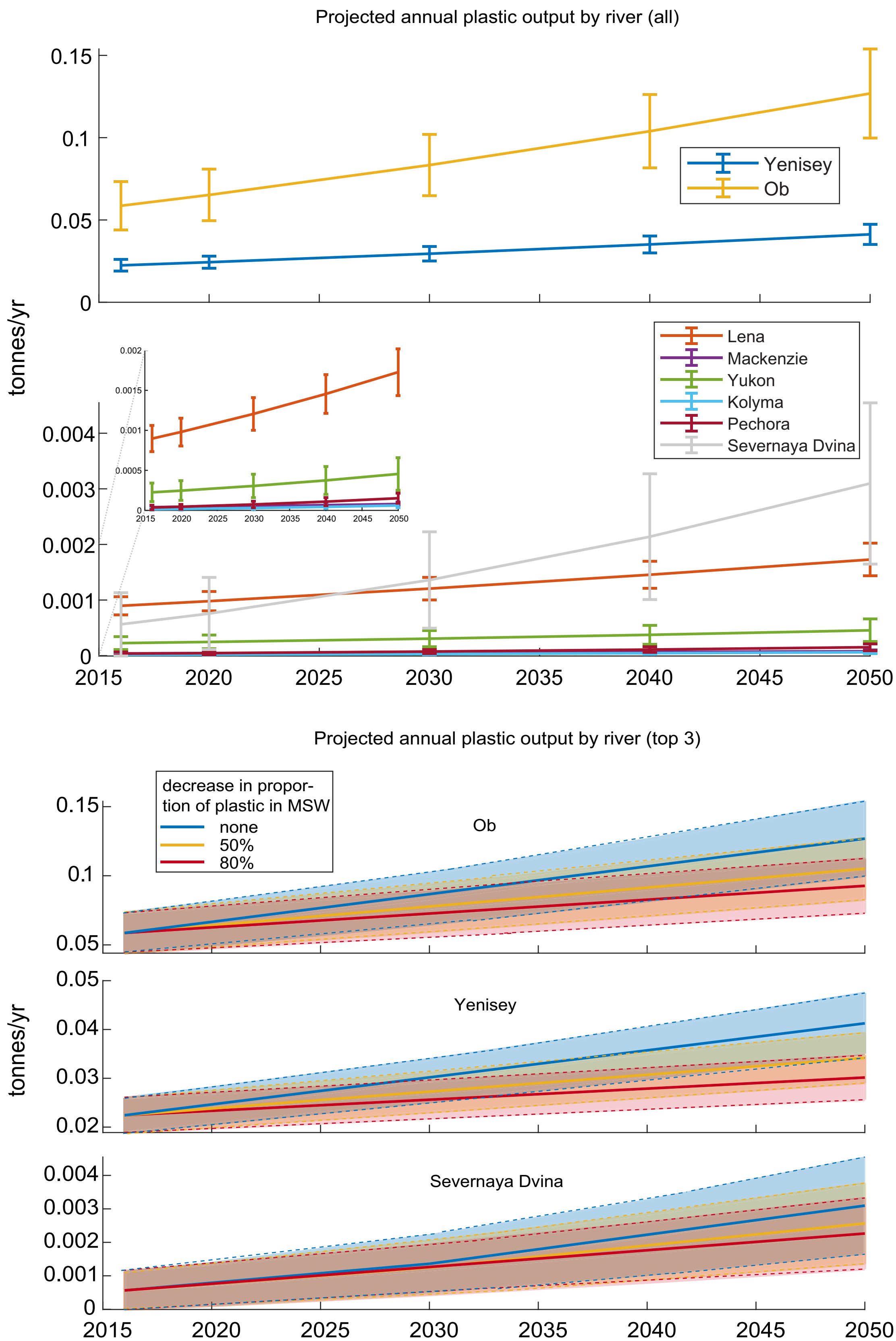

Figure 2. Plastic export from Rivers including decadal projections. Plastic input to the Arctic Ocean from the eight largest rivers. *Top:* Each river's current and projected plastic flux, based on trends in population, river flow, and mass of municipal solid waste. *Bottom:* Projections for the three largest riverine plastic contributors under reduced plastic scenarios. Here, "MSW" refers to municipal solid waste. Shading indicates projected uncertainty.

https://doi.org/10.1017/S0032247423000268 Published online by Cambridge University Press

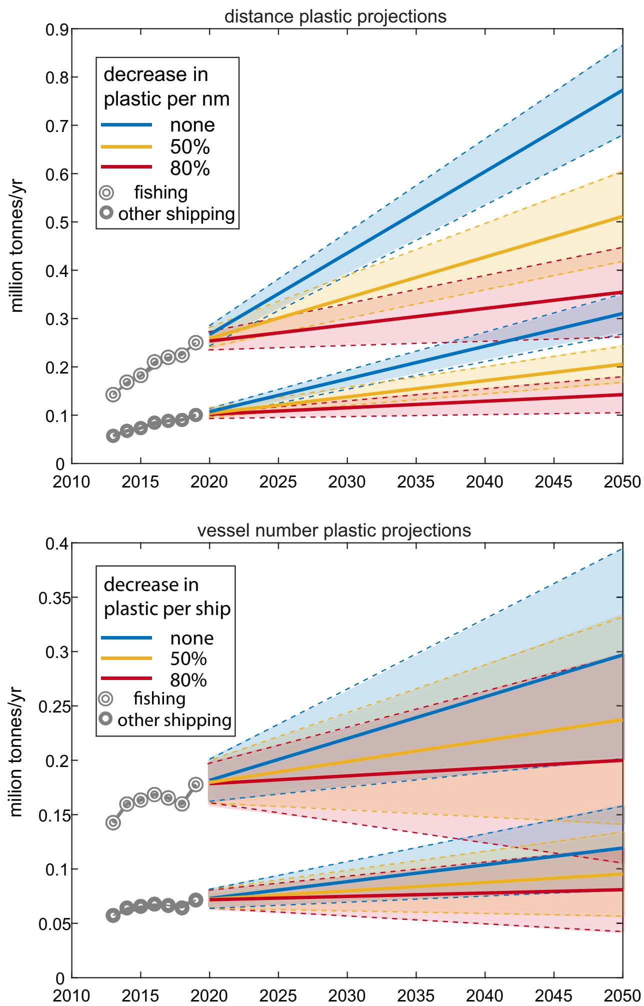

Figure 3. Shipping & Fishing plastic fluxes including decadal projections. Plastic input to the Arctic Ocean from fishing vessels and all other shipping vessels under reduced plastic scenarios. Projections are calculated both by distance (*top*; plastic per nautical mile traveled) and individual vessels (*bottom*). Shading indicates projected uncertainty.

Arctic and near-Arctic ports for the deposit of plastic. An example of this already occurs in Iceland, where fishing nets may be deposited at coastal collection stations for recycling (https://www.urvinnslusjodur.is/voruflokkar/#veidarfaeri). Any money forfeited by ships would be used to cover the cost of beach clean-ups, providing waste disposal for Arctic communities and other projects which will reduce the amount of plastic in the Arctic Ocean. This would work alongside the provisions of MARPOL Annex V, such as the requirement for garbage disposal at ports and the Polar Code, with ships requiring a plastic permit alongside, or as part of, their Polar Code registration.

Recommended conservation component to tourism: Tourism is already a growing industry within the Arctic and much of the tourist access to the Arctic is by way of cruise ships. It is recommended that all tourist and cruise ships over a certain (small) size should be encouraged, or ideally required, to include an element of conservation, with guests invited to take part in clearing beaches of plastic debris, similar to the Association of Arctic Expedition Cruise Operators' Clean Up Svalbard Project, which removes tens of tonnes of waste from archipelago beaches annually (https://www.aeco.no/guidelines/cleanup-guidelines/). One of the benefits of using cruise ships is that they are able to access remote beaches beyond settlements. Tourists in the Arctic are increasingly aware of their impact on the environment and many would appreciate the opportunity to take practical action to protect the environment.

Working toward the prohibition of the use of certain plastics within the Arctic Ocean: One example would be a requirement that all fishing nets must be made from a material other than plastic. Biodegradable nets, in materials such as hemp, are being developed and while they will be expensive at first, Arctic fishing is predicted to be a lucrative industry which will be able to support the cost if compelled to do so. Money from the plastic permitting scheme mentioned above could be used to pay for biodegradable nets for small scale fishermen. As there is currently a moratorium on fishing in the Central Arctic Ocean which will not expire until 2035, as well as bans on commercial fishing in the Arctic territorial waters of the USA and Canada, there is an opportunity to put in place regimes which reduce the amount of plastic being introduced to the Arctic marine environment from the start rather than requiring an already established industry to change.

MSW handling: Improving sanitation infrastructure and waste management for remote communities will decrease riverine plastic input to the Arctic Ocean. While this source of plastic is dwarfed by other inputs, settlements are clear point sources at which to address the problem with high rates of success. Long a source of concern for public health and economic reasons, the dearth of sanitary infrastructure in many of these communities provides an opportunity for plastic pollution mitigation as well.

Intervention quantification

The international agreements discussed form the background of marine pollution interventions, yet the true test of their efficacy is how much plastic they would actually keep from the ocean. Here we map each intervention to its affected pathway, the order of magnitude of projected plastic flux change, and the expected efficacy of each intervention (Table 2).

Efficacies are sorted into high, medium, and low, based on anticipated community buy-in as well as enforceability under international law. While qualitative estimates, these efficacy levels are based on technical discussions of policy compliance across fishing, (Expert Consultation on the Marking of Fishing Gear & Food and Agriculture Organization of the United Nations, 2016; Technical Consultation on Marking of Fishing Gear & Food and Agriculture Organization of the United Nations, 2018) consumer behavior (Ajayi & Reiner, 2020; Zwicker et al., 2021) and party States (Fritz, 2020). For example, beach cleanups may be popular but they are unenforceable and challenging due to remoteness, earning a medium rating. They also have a relatively small impact on the magnitude of plastic pollution. Thus we suggest that a future reduction scenario is the 20% pathway described in Fig. 2.

Conclusion

This manuscript is a first, simplified attempt to quantify plastic fluxes of and various interventions regarding plastic in the Arctic Ocean. While it is clear that more in-situ measurement of plastic concentrations are necessary to fully describe the movement of these pollutants into and out of the Arctic system, the calculations presented in this paper give an overview of the magnitude of the problem, describe the scale of the major inputs of plastic into the Arctic Ocean and, importantly, provide both suggestions for actions which could be taken to ameliorate the levels of plastic in the Arctic ocean and attempt to quantify the impact which each of these would have. Due to point sources such as ships and rivers, as well as variable mesoscale ice and ocean structure, the inherent patchiness in plastic concentration and the continued decline of the sea ice cover mean that the fundamental physical behavior of plastic in the Arctic Ocean will continue to evolve.

Despite the ubiquity of plastic pollution in the Arctic marine environment, the problem is not intractable. Existing governance structures and international agreements have the potential for effective use as tools to decrease the amount of plastic in the Arctic Ocean. These agreements are valuable because they solve a regional problem across national legal structures, and have a degree of enforceability lacking in such good-faith action plans as that of the Arctic Council. We have described a series of interventions built on the legal foundation of these treaties, and quantified their impact on plastic fluxes; given the outsized influence of shipping and fishing on the introduction of plastic pollution to the Arctic Ocean, we find interventions targeting these sectors to be most effective.

Acknowledgments. *The authors wish to thank the Editor as well as two anonymous reviewers for giving their time and energy to the improvement of this manuscript.*

Financial support. *This work was supported by the Gordon and Betty Moore Foundation (grant number GBMF7965) and by the Schmidt Futures Initiative.*

Competing interests. The authors declare no conflicts of interest.

References

Aagaard, K., & Carmack, E. C. (1989). The role of sea ice and other fresh water in the Arctic circulation. *Journal of Geophysical Research*, *94*(C10), 14485. doi: 10.1029/JC094iC10p14485

Ajayi, V., & Reiner, D. (2020). *Consumer Willingness to Pay for Reducing the Environmental Footprint of Green Plastics.* (n.d.). https://doi.org/10.17863/CAM.62845

Amaral-Zettler, L. A., Zettler, E. R., & Mincer, T. J. (2020). Ecology of the plastisphere. *Nature Reviews Microbiology*, *18*(3), 139–151.

Ambrosini, R., Azzoni, R. S., Pittino, F., Diolaiuti, G., Franzetti, A., & Parolini, M. (2019). First evidence of microplastic contamination in the supraglacial debris of an alpine glacier. *Environmental Pollution*, *253*, 297–301. doi: 10.1016/j.envpol.2019.07.005

Amélineau, F., Delphine Bonnet, O. H., Valentine Mortreux, A. M. A., Harding, N. K., Walkusz, W., Fort, J., & Grémillet, D. (2016). Microplastic pollution in the Greenland Sea: Background levels and selective contamination of planktivorous diving seabirds. *Environmental Pollution*, *219*, 1131–1139.

Ask, A., Anker-Nilssen, T., Herzke, D., Trevail, A., van Franeker, J. A., & Gabrielsen, G. W. (2016). *Contaminants in Northern Fulmars (Fulmarus Glacialis) Exposed to Plastic*: Nordic Council of Ministers. doi: 10.6027/TN2016-543

Barboza, L. G. A., Vethaak, A. D., Lavorante, B. R. B. O., Lundebye, A.-K., & Guilhermino, L. (2018). Marine microplastic debris: An emerging issue for food security, food safety and human health. *Marine Pollution Bulletin*, *133*, 336–348.

Barnes, D. K. A. (2002). Invasions by marine life on plastic debris. *Nature*, *416*(6883), 808–809. doi: 10.1038/416808a

Barnes, D. K. A., & Milner, P. (2005). Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Marine Biology*, *146*(4), 815–825. doi: 10.1007/s00227-004-1474-8

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G. W., Provencher, J. F., Rochman, C. M., . . . , & Tekman, M. B. (2022). Plastic pollution in the Arctic. *Nature Reviews Earth & Environment* *3*(5), 323–337.

Bergmann, M., Lutz, B., Tekman, M. B., & Gutow, L. (2017). Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. *Marine Pollution Bulletin*, *125*(1–2), 535–540.

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

Blunden, J., & Arndt, D. S. (2019). State of the climate in 2018. *Bulletin of the American Meteorological Society*, *100*(9), Si–S306. doi: 10.1175/2019BAMSStateoftheClimate.1

Bogoyavlenskiy & Siggner (2004). Arctic demography. In *AHDR (Arctic Human Development Report*). Akyreyri: Stefansson Arctic Institute, (n.d.).

Carmack, E. C. (2000). The Arctic Ocean's Freshwater Budget: Sources, storage and export. In E. L. Lewis, E. P. Jones, P. Lemke, T. D. Prowse, & P. Wadhams (Eds.), *The Freshwater Budget of the Arctic Ocean* (pp. 91–126): Springer Netherlands. doi: 10.1007/978-94-011-4132-1_5

Chassignet, E. P., Xu, X., & Zavala-Romero, O. (2021). Tracking Marine Litter with a global ocean model: Where does it go? Where does it come from? *Frontiers in Marine Science*, *8*, 667591. doi: 10.3389/fmars.2021.667591

Cózar, A., Martí, E., Duarte, C. M., García-de-Lomas, J., van Sebille, E., Ballatore, T. J., . . . , & Irigoien, X. (2017). The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation. *Science Advances*, *3*(4), e1600582. doi: 10.1126/sciadv.1600582

Cózar, A., Fidel Echevarría, J., González-Gordillo, I., Irigoien, X., Úbeda, B., Hernández-León, S., . . . , & Duarte, C. M. (2014). Plastic debris in the open ocean. *Proceedings of the National Academy of Sciences* *111*(28), 10239–10244.

Curry, B., Lee, C. M., Petrie, B., Moritz, R. E., & Kwok, R. (2014). Multiyear volume, liquid freshwater, and sea ice transports through Davis Strait, 2004–10*. *Journal of Physical Oceanography*, *44*(4), 1244–1266. doi: 10.1175/JPO-D-13-0177.1

DeRepentigny, P., Jahn, A., Tremblay, L. B., Newton, R., & Pfirman, S. (2020). Increased transnational sea ice transport between neighboring Arctic states in the 21st century. *Earth's Future*. doi: 10.1029/2019EF001284

Dickson, R. R., Meincke, J., & Rhines, P. (Eds.). (2008). *Arctic-Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate*. Dordrecht, Netherlands: Springer.

Eguíluz, V. M., Fernández-Gracia, J., Irigoien, X., & Duarte, C. M. (2016). A quantitative assessment of Arctic shipping in 2010–2014. *Scientific Reports*, *6*(1), 30682. doi: 10.1038/srep30682

Sherrington, C. (2016). *Plastics in the Marine Environment*. Eunomia Research & Consulting Ltd. p. 13.

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

Expert Consultation on the Marking of Fishing Gear & Food and Agriculture Organization of the United Nations. (2016). *Report of the Expert Consultation on the Marking of Fishing Gear: Rome, 4–7 April 2016*. http://bibpurl.oclc.org/web/80689; http://www.fao.org/3/a-i5729e.pdf

Fritz, J.-S. (2020). Governing plastics pollution in the ocean: From Anarchy to mission orientation. *Ocean Yearbook Online*, *34*(1), 231–254. doi: 10.1163/9789004426214_010

GESAMP (2019). *Guidelines or the Monitoring and Assessment of Plastic Litter and Microplastics in the Ocean* (Kershaw P. J., Turra A. and Galgani F. editors), (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). *Rep. Stud.* GESAMP No. 99, 130p. (n.d.).

Greene, C. A., Gwyther, D. E., & Blankenship, D. D. (2017). Antarctic mapping tools for Matlab. *Computers & Geosciences*, *104*, 151–157. doi: 10.1016/j.cageo.2016.08.003

Holmes, R. M., Shiklomanov, A. I., Tank, S. E., McClelland, J. W., and Tretiakov, M. (2015) River discharge. In *Arctic Report Card: Update for 2015*. (n.d.). https://arctic.noaa.gov/Report-Card/Report-Card-2015/ArtMID/5037/ArticleID/227/River-Discharge.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., . . . , & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, *347*(6223), 768–771. doi: 10.1126/science.1260352

Jang, Y. C., Lee, J., Hong, S., Mok, J. Y., Kim, K. S., Lee, Y. J., Choi, H.-W., Kang, H., & Lee, S. (2014). Estimation of the annual flow and stock of marine debris in South Korea for management purposes. *Marine Pollution Bulletin*, *86*(1–2), 505–511. doi: 10.1016/j.marpolbul.2014.06.021

Kanhai, L. D. K., Gårdfeldt, K., Lyashevska, O., Hassellöv, M., Thompson, R. C., & O'Connor, I. (2018). Microplastics in sub-surface waters of the Arctic Central Basin. *Marine Pollution Bulletin*, *130*, 8–18. doi: 10.1016/j.marpolbul.2018.03.011

Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank. doi: 10.1596/978-1-4648-1329-0

Lahn, B. (2020). A history of the global carbon budget. *Wiley Interdisciplinary Reviews: Climate Change*, *11*(3), e636.

Larsen, J. N., & Fondahl, G. (2015). *Arctic Human Development Report*: Nordic Council of Ministers. doi: 10.6027/TN2014-567

Lebreton, L., & Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, *5*(1), 6. doi: 10.1057/s41599-018-0212-7

Lebreton, L. C. M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications*, *8*(1), 15611. doi: 10.1038/ncomms15611

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

Mu, J., Zhang, S., Qu, L., Jin, F., Fang, C., Ma, X., … , & Wang, J. (2019) Microplastics abundance and characteristics in surface waters from the Northwest Pacific, the Bering Sea, and the Chukchi Sea. *Marine Pollution Bulletin*, *143*, 58–65.

Newton, R., Pfirman, S., Tremblay, B., & DeRepentigny, P. (2017). Increasing transnational sea-ice exchange in a changing Arctic Ocean. *Earth's Future*, *5*(6), 633–647. doi: 10.1002/2016EF000500

Obbard, R. W., Sadri, S., Wong, Y. Q., Khitun, A. A., Baker, I., & Thompson, R. C. (2014). Global warming releases microplastic legacy frozen in Arctic Sea ice. *Earth's Future*, *2*(6), 315–320.

Østerhus, S., Woodgate, R., Valdimarsson, H., Turrell, B., De Steur, L., Quadfasel, D., … , & Berx, B. (2019). Arctic Mediterranean exchanges: a consistent volume budget and trends in transports from two decades of observations. *Ocean Science*, *15*(2), 379–399.

PAME- Arctic Shipping Status Report #1. (n.d.). https://arcg.is/GjqPG

PAME, Desktop Study on Marine Litter including Microplastics in the Arctic (May 2019). (n.d.).

PAME, Regional Action Plan on Marine Litter in the Arctic. (May 2021).

Parga Martínez, K. B., Tekman, M. B., & Bergmann, M. (2020). Temporal trends in Marine Litter at three stations of the HAUSGARTEN observatory in the Arctic deep sea. *Frontiers in Marine Science*, *7*, 321. doi: 10.3389/fmars.2020.00321

Peeken, I., Bergmann, M., Gerdts, G., Katlein, C., Krumpen, T., Primpke, S., & Tekman, M. B. (2018). *Microplastics in the Marine Realms of the Arctic with Special Emphasis on Sea Ice*. (https://www.arctic.noaa.gov/Report-Card), Arctic Report Card, 2018, pp. 89–99.

Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., … , & Gerdts, G. (2018). Arctic sea ice is an important temporal sink and means of transport for microplastic. *Nature Communications*, *9*(1), 1505. doi: 10.1038/s41467-018-03825-5

Provencher, J. F., Bond, A. L., Avery-Gomm, S., Borrelle, S. B., Bravo Rebolledo, E. L., Hammer, S., … & van Franeker, J. A. (2017). Quantifying ingested debris in marine megafauna: A review and recommendations for standardization. *Analytical Methods*, *9*(9), 1454–1469. doi: 10.1039/C6AY02419J

Rogelj, J., Schaeffer, M., Friedlingstein, P., Gillett N. P., Van Vuuren, D. P., Riahi, K., … , & Knutti R. (2016). Differences between carbon budget estimates unravelled. *Nature Climate Change*, *6*, 245–252. doi: 10.1038/nclimate2868

Ross, P. S., Chastain, S., Vassilenko, E., Etemadifar, A., Zimmermann, S., Quesnel, S.-A., … , & Williams, B. (2021). Pervasive distribution of polyester fibres in the Arctic Ocean is driven by Atlantic inputs. *Nature Communications*, *12*(1), 106.

Serreze, M. C., Barrett, A. P., Slater, A. G., Woodgate, R. A., Aagaard, K., Lammers, R. B., … & Lee, C. M. (2006). The large-scale freshwater cycle of the Arctic. *Journal of Geophysical Research*, *111*(C11). doi: 10.1029/2005JC003424

Sherman, P., & van Sebille, E. (2016). Modeling marine surface microplastic transport to assess optimal removal locations. *Environmental Research Letters*, *11*(1), 014006. doi: 10.1088/1748-9326/11/1/014006

Shiklomanov, A. I., Holmes, R. M., McClelland, J.W., Tank, S.E., and Spencer, R.G.M. (2021). *Arctic Great Rivers Observatory. Discharge Dataset, version 20200604*. (n.d.). https://www.arcticrivers.org/data.

Shiklomanov, A. I., Yakovleva, T. I., Lammers, R. B., Karasev, I. P., Vörösmarty, C. J., & Linder, E. (2006). Cold region river discharge uncertainty—Estimates from large Russian rivers. *Journal of Hydrology*, *326*(1–4), 231–256. doi: 10.1016/j.jhydrol.2005.10.037

Spreen, G., Steur, L., Divine, D., Gerland, S., Hansen, E., & Kwok, R. (2020). Arctic Sea Ice volume export through Fram Strait from 1992 to 2014. *Journal of Geophysical Research: Oceans*, *125*(6). doi: 10.1029/2019JC016039

Technical Consultation on Marking of Fishing Gear & Food and Agriculture Organization of the United Nations (Eds.). (2018). *Report of the Technical Consultation on Marking of Fishing Gear: Rome, 5–9 February 2018*.

Tekman, M. B., Wekerle, C., Lorenz, C., Primpke, S., Hasemann, C., Gerdts, G., & Bergmann, M. (2020). Tying up loose ends of microplastic pollution in the arctic: Distribution from the Sea surface through the water column to Deep-Sea sediments at the HAUSGARTEN observatory. *Environmental Science & Technology*, *54*(7), 4079–4090. doi: 10.1021/acs.est.9b06981

Trevail, A. M., Gabrielsen, G. W., Kühn, S., & Van Franeker, J. A. (2015). Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (Fulmarus glacialis). *Polar Biology*, *38*(7), 975–981. doi: 10.1007/s00300-015-1657-4

Tsubouchi, T., Bacon, S., Aksenov, Y., Naveira Garabato, A. C., Beszczynska-Möller, A., Hansen, E., … , & Lee, C. M. (2018). The Arctic Ocean seasonal cycles of heat and freshwater fluxes: Observation-Based inverse estimates. *Journal of Physical Oceanography*, *48*(9), 2029–2055.

Turrell, W. R. (2020). Estimating a regional budget of marine plastic litter in order to advise on marine management measures. *Marine Pollution Bulletin*, *150*, 110725. doi: 10.1016/j.marpolbul.2019.110725

van Franeker, J. A., & Law, K. L. (2015). Seabirds, gyres and global trends in plastic pollution. *Environmental Pollution*, *203*, 89–96. doi: 10.1016/j.envpol.2015.02.034

van Sebille, E., Aliani, S., Law, K. L., Maximenko, N., Alsina, J., Bagaev, A., … & Wichmann, D. (2020). The physical oceanography of the transport of floating marine debris. *Environmental Research Letters*. doi: 10.1088/1748-9326/ab6d7d

Vethaak, A. D., & Leslie, H. A. (2016). *Environmental Science & Technology* *50*(13), 6825–6826. doi: 10.1021/acs.est.6b02569

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

Woodgate, R. A. (2018). Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. *Progress in Oceanography*, *160*, 124–154. doi: 10.1016/j.pocean.2017.12.007

Wright, R. J., Erni-Cassola, G., Zadjelovic, V., Latva, M., & Christie-Oleza, J. A. (2020). Marine plastic debris: A new surface for microbial colonization. *Environmental Science & Technology*, *54*(19), 11657–11672.

Zwicker, M. V., Brick, C., Gruter, G.-J. M., & van Harreveld, F. (2021). (Not) doing the right things for the wrong reasons: An investigation of consumer attitudes, perceptions, and willingness to pay for bio-based plastics. *Sustainability*, *13*(12), 6819. doi: 10.3390/su13126819