Microplastics and Nanoplastics

PERSPECTIVE

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Legacy oceanic plastic pollution must be addressed to mitigate possible long-term ecological impacts

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Abstract

Scientific research over the past decade has demonstrated that plastic in our oceans has detrimental consequences for marine life at all trophic levels. As countries negotiate an international legally binding instrument on plastic pollution, the focus is on eliminating plastic emissions to the environment. Here, we argue that, while this endeavour is urgently needed to limit the negative impacts of plastic on ocean ecosystems, the reduction of the plastic flow to the environment should not be the sole purpose of the negotiations. Legacy oceanic plastic pollution is also a major concern that needs to be addressed in the coming Treaty. Plastic is ubiquitous and persistent in the environment, and its slow degradation produces uncountable amounts of potentially even more impactful micro- and nanoparticles. Thus, plastic that is already present in the oceans may continue to affect ecosystems for centuries. Recent global assessments reveal that microplastics could have a significant impact on biogeochemical cycles and microbial food chains within ocean ecosystems that may be equivalent to those of climate change. Therefore, we argue that cleanup initiatives are essential to avoid further longterm impacts of legacy oceanic pollution. The upcoming international negotiations to develop a new Global Plastics Treaty should aim at urgently reducing the flow of plastic to the marine environment while supporting innovative solutions towards efficient monitoring and cleanup of the legacy oceanic plastic pollution.

Keywords Ocean plastic pollution, Global plastics treaty, Marine ecosystems, Plastic cleanups, Legacy oceanic plastic pollution, Ecological impacts

Introduction

Over the past decades, the steep increase in ocean plastics contamination has raised concerns in the scientific community as well as among the public [1–4]. The visible impacts of plastic pollution on ocean ecosystems and economic sectors have led to calls for urgent action to address this pressing issue [5, 6]. At an international level, UNEA Resolution 5/14 was adopted in March 2022 to develop a new legally binding instrument to end plastic pollution, including in the marine environment [7]. An Intergovernmental Negotiating Committee was established to guide the negotiation process, with the aim to complete the negotiations by the end of 2024. At the national level, countries attempt to address environmental plastic pollution via a multitude of legislative approaches including the phase out of single-use plastics and levies to discourage their use and/or to encourage their recycling [8–10]. Such efforts largely target

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reducing the flow of plastics into the environment, particularly into our oceans.

Every year, the global flow of plastic into the ocean from land is estimated between 0.1 and 23 million metric tons (MT) [11]. Most of this pollution is linked with inadequate waste management [12], and the current commitments of countries towards waste reduction are insufficient to tackle the continued increase in global plastic production [13]. Plastic emissions from marine activities such as fishing and shipping remain poorly quantified but have been estimated to range around 0.2 to 0.6 MT per year [14]. While production control and emission reduction are unarguably essential to avoiding further contamination, they do not address impacts of plastics that have already accumulated in the ocean, and for which any preventive actions come too late. This so-called legacy oceanic plastic pollution is defined as the aggregated mass of plastic emitted from rivers and coastlines, or that was lost, abandoned, or otherwise discarded, into coastal waters and ocean, including areas beyond national jurisdiction. An estimated 0.6 to 2.0 MT of plastics is currently floating at the ocean surface globally, with most of this plastic mass contained in larger objects [14, 15]. These plastic items are likely to persist at the ocean surface for decades or longer, slowly degrading into potentially impactful micro- and nanoplastics [15–17]. In this light, various initiatives to address this legacy pollution problem in the marine environment have emerged [18]. The most frequent method is plastic cleanup either at the coast, the river mouth or at the sea surface [19]. However, concerns are raised related to the efficiency of such efforts relative to their carbon emissions and potential impact on the local ecosystem by entrapping marine life [20, 21].

In this Perspective, we argue that to efficiently tackle plastic pollution in the oceans, international negotiations should aim at stopping the flow of plastic into the environment as quickly as possible. However, this measure, even if successful, can not address the legacy oceanic plastic pollution. Mounting evidence of adverse ecological and biological consequences of microplastics contamination suggests that measures to avoid environmental fragmentation of legacy pollution and to follow the precautionary principle in relation to human health and marine life is warranted. If we don't act now, we may never be able to do so in the future because the plastic will go further into the water column, out of reach for any viable remediation strategy. Thus, collective action should be taken for the remediation of legacy oceanic plastic pollution, while at the same time implementing upstream and midstream measures. Global support towards innovative, scalable and environmentally sound cleanup solutions is necessary to help mitigate negative impacts of plastic already accumulated in our oceans.

The environmental impacts of ocean plastic pollution

Ocean plastic pollution has clear detriments to marine ecosystems. Plastic in our oceans impacts marine life through many processes involving ingestion [22], entanglement [23], distribution of invasive and potentially harmful organisms and pathogens [24], and the release of chemicals [25, 26] (Fig. 1). Furthermore, negative impacts of plastic pollution on marine wildlife directly threatens commercial activities such as fisheries and tourism [6, 27]. Plastic pollution regularly causes damage to fishing gear and vessels as well as a general degradation of fish quality and quantity, with direct consequences for the economic sustainability of marine activities [28, 29].

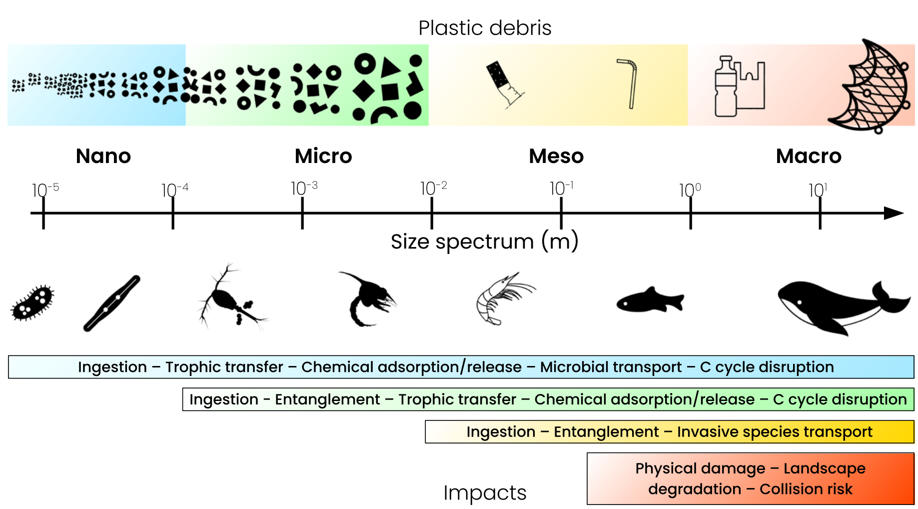

Fig. 1 Size dependent environmental impacts of plastic debris. The colour bars represent the species impacted by each plastic size class

Furthermore, plastic pollution may directly threaten human health and recreational grounds through the transport of pathogens by plastic debris [24, 30, 31] and through translocation of nano-sized particles in humans [32, 33].

Besides entanglement of marine life in larger plastic items, particularly abandoned, lost or discarded fishing gear, one of the most important aspects of plastic pollution is fragmentation of larger plastic items into uncountable micro- and nano-plastic particles [17, 34]. Although micro- and nano-sized plastics make up a small portion of the total mass of plastic pollution in the ocean [14], they may be responsible for a significant part of the damage [35]. As plastics fragment into smaller microplastics, they lose buoyancy and begin to trace neutrally [36, 37]. Consequently, micro- and nanoplastics are redistributed by ocean currents and are found in every region of the ocean [38–42]. Thus, they may affect all trophic levels, from mammals to plankton [43–45]. Additionally, their large surface to volume ratio makes them particularly susceptible to the transport and release of contaminants, nutrients, and to the formation of biofilm [46–48]. Stimulation of algal growth by microplastics is widely reported which has implications for nutrient cycling [49].

Recently, global biogeochemical models have been developed to study the potential impacts of microplastics at the global scale [38, 50]. These models enable researchers to study the global distribution and seasonal variations of microplastics, plankton, and nutrients. A first global assessment revealed that the seasonal peak in zooplankton grazing rates coincides with that of microplastic concentration in over 25% of the ocean surface [38]. This suggests that zooplankton, keystone species in the ocean, are potentially significantly exposed to the impacts of microplastics. A different model study estimated that microplastic-slowed fecal pellet sinking could produce an up to 30% reduction in fecal pellet fluxes and a more than 50% increase in other organic detrital fluxes in a business-as-usual increasing pollution scenario [50]. Furthermore, ecological shifts due to shoaling of nutrient remineralization impacted the competitive advantage between functional groups, suggesting shifting selective pressure altering winners and losers in the presence of microplastics [50].

While global scale model development of plastic-biological interactions is still in its early days, multiple models using a diversity of approaches produce non-negligible biogeochemical impacts at regional to global scale. To date, the modeling of ecological and biogeochemical impacts of open ocean microplastic pollution suggests significant impacts may occur in gyres because of the exceptionally high concentrations of microplastic found in those regions [38]. But other regions such as the biologically productive North Pacific and North Atlantic/North Sea, as well as coastal areas that retain high amounts of plastic waste may also be impacted [38, 50]. Water column contamination exposes poorly understood ocean ecosystems, such as the meso- and bathypelagic to unknown ill effects. These environments are very sensitive to perturbation and are also tightly coupled to ocean carbon cycling. These findings suggest that ocean microplastic contamination has the potential to cause widespread, poorly reversible, and long-term impacts on marine ecosystems. The potential for long-term ecological impacts of microplastics (including in areas beyond national jurisdiction) carries far-ranging socioeconomic implications that must be considered when formulating policy.

Current applications and benefits of plastics removal

The scientific consensus is clear: plastic pollution is a major threat to ocean ecosystems, and we must take action to limit it [51–53]. One of the main solutions put forward during the ongoing negotiations of a Global Plastics Treaty is to put a rapid end to plastic emissions into the environment. The success of this ambitious goal is an undeniable necessity. Yet, scientific research has demonstrated that the large amount of plastic that has already reached the ocean will continue to impact the ecosystems for centuries [16, 54–56]. Figure 2 illustrates the dispersal of floating plastic debris in the global ocean by comparing simulated ocean contamination with, and without land-based plastic emissions. It shows that legacy oceanic plastic pollution remaining in our oceans after turning off plastic emissions from land will either beach back to land or concentrate in subtropical oceanic gyres. Recent research revealed that plastic debris afloat in these offshore waters can persist for decades or longer [14, 15, 57]. Thus, even with immediate land-based flux elimination, the level of microplastics in the ocean could double by mid-century due to the slow degradation of larger legacy plastics into smaller pieces [15]. Mitigating microplastic pollution in the global ocean therefore requires a drastic reduction in emissions of plastic pollution in combination with active removal of larger plastic items already present in the ocean to reduce further generation of secondary microplastics for the decades to come (Fig. 3). In this context, it is essential that remediation solutions for legacy oceanic plastic pollution within and beyond areas of national jurisdiction be proposed during negotiations, and that the upcoming Global Plastics Treaty addresses this issue, adopting the technology neutrality principle. The technology neutrality principle implies applying no constraints or prescriptions on choices of technology or equipment, and not favouring nor discriminating against any technology. Moreover, before deployment, each

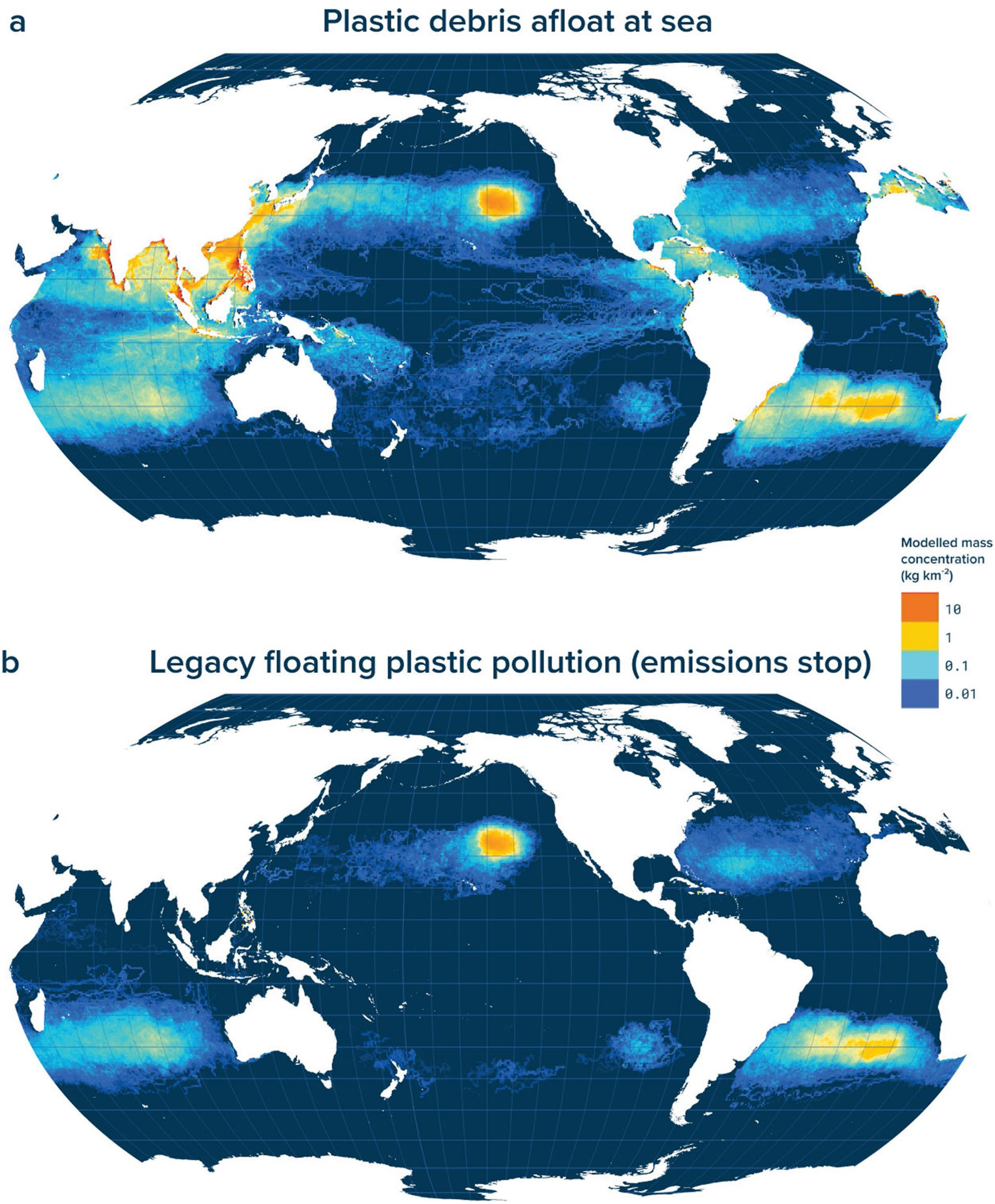

Fig. 2 **a** Modelled distribution of plastic debris afloat at sea. **b** Legacy oceanic plastic pollution remaining in our oceans after turning off plastic emissions from land. Model particles are advected using data on sea surface circulation following the methodology of Lebreton et al. 2012 [58], from significant inland sources of plastic pollution as reported in Meijer et al. 2021 [59]. A beaching term is added using the formulation presented in Lebreton et al. 2022 [60] to represent the stranding of floating debris. Particles are continuously released from 1993 to 2020 in (**a**) while the influx of modelled debris is stopped from 2010 in (**b**). Results are presented for the year 2020

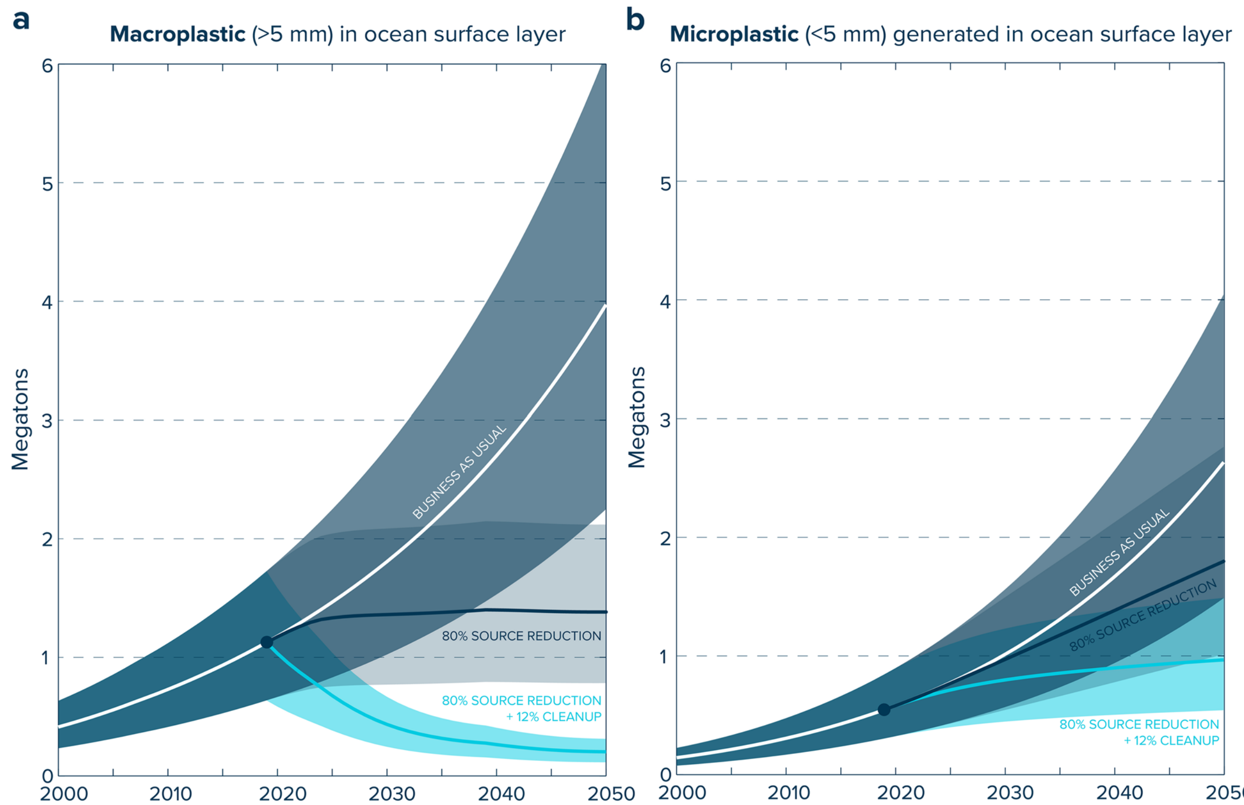

Fig. 3 Future projections for accumulated mass of buoyant (**a**) macroplastic (i.e., plastic items > 5 mm) and (**b**) secondary microplastics (i.e., plastic fragments < 5 mm generated by degradation of macroplastics) at the ocean surface under three scenarios: (1) business as usual (i.e., emissions increase at average 2005–2015 growth rate), (2) 80% emission reduction from 2020, and (3) 80% emission reduction from 2020 combined with a 12% annual cleanup of macroplastics. These scenarios are based on the global degradation and circulation model by Lebreton et al. (2019) [15]

remediation technology should be assessed by conducting an Environmental Impact Assessment and by subsequently developing an Environmental Management Plan to monitor and mitigate potentially adverse impacts during operations [19].

Removing plastic accumulated in offshore areas reduces harm from entanglement, ingestion, and invasive species transport, as well as the risks for human health (reducing human exposure to pathogens found on ocean plastic via seafood consumption or direct contact with ocean plastic). Furthermore, it decreases costs to small island states (which receive large amounts of plastic from the gyres) [61], to marine traffic (entanglement and collision, increased insurance costs) [29], and to coastal communities (beach cleanups, decreased tourism) [28, 62]. Overall, marine plastic pollution represents an avoidable cost to society [63]. Thus, avoiding plastic pollution through flux reduction and cleanup should bring immediate economic benefits.

In the open ocean, the majority of plastic cleanups target the surface of the gyres which are convergence zones, concentrating the highest amounts of floating plastic debris [64, 65]. In these areas surface plastic removal limits the risks of ventilating plastic pollution towards the deeper layers [66]. Thus, surface ocean cleanups may bring long-term significant ecological and economic benefits. Finally, oceanic gyres are the main areas of accumulation for positively buoyant and persistent legacy oceanic plastic pollution (Fig. 2). Therefore, ecological impacts of plastic pollution in these regions may be observed for decades, even after stopping plastic emissions to the ocean (Fig. 3). Thus, the surface of oceanic gyres are particularly sensitive to the impacts of legacy plastic pollution and surface cleanups could efficiently mitigate these impacts.

Challenges and recommendations

The Global Plastics Treaty must prioritize stopping the flow of plastic into the ocean. However, it must also address the legacy oceanic plastic pollution, particularly in plastic accumulation hotspots. A major fraction of positively buoyant plastic debris ends up on beaches and coasts [15, 67]. Coastal environments are therefore significant plastic accumulation zones and targeted by a variety of beach cleanup or dive against debris activities worldwide [19, 52, 61]. However, such efforts are largely conducted by manual labour and run on a voluntary basis, without coordinated oversight. Many coastal areas are difficult to access and therefore remain largely unaddressed by manual cleanups.

In the open ocean, the highest levels of plastic pollution are found in the subtropical oceanic gyres [19, 62, 68]. Initiatives such as The Ocean Cleanup have started to remove legacy plastic pollution from the North Pacific subtropical gyre, the largest accumulation zone of floating plastic debris in the ocean, also termed the Great Pacific Garbage Patch. Such cleanup efforts have been met with some criticism due to the potential for unintentional damage associated with possible bycatch of marine life and the release of greenhouse gases into the atmosphere [19]. However, open ocean cleanup is a complex issue with both potential benefits and drawbacks. The negative impacts of plastic pollution on marine ecosystems are already well-documented, and the long-term impacts of inaction towards legacy oceanic plastic pollution are potentially significant and irreversible. Thus, impact assessments of cleanup technologies should assess the net environmental gain by evaluating both the negative impacts occurring during cleanup as well as the harm reduction achieved by mitigating the negative impacts associated with plastic pollution. In this context, legislation on plastic pollution must be based on a careful consideration of all options, including the costs and benefits of different clean-up methods against not acting at all, and taking into account all future socio-economic scenarios regarding plastic production and waste management.

Cleanup initiatives in the marine environment are currently mostly limited to beaches, the sea surface, and the shallow seabed. No efficient and environmentally-sound method seems to exist to address the legacy pollution beyond a few meters water depth nor from micro- and nanoplastics. Nature-based solutions are a promising example for the latter [69]. Yet, significant research and developments are required to further explore such solutions.

When considering the vastness of legacy oceanic plastic pollution, substantial funding and policy support are necessary to continue the current cleanup efforts and to find additional innovative solutions to tackle the legacy oceanic plastic pollution at scale. The responsibility of cleaning up this tremendous amount of legacy plastic in our ocean can not rely solely on NGOs, non-profit organizations, and voluntary citizens [5]. We need concerted efforts from all countries working together to coordinate and fund this essential work. The Global Plastics Treaty is an opportunity to encourage policy decisions that address the issue of legacy oceanic plastic pollution, including in areas beyond national jurisdiction, and to provide the necessary financial and institutional means. This includes scaling up and organizing cleanup operations, developing new technologies for removing plastic pollution, and creating incentives for the reduction and mitigation of plastics. We argue that priority should be given to cleanup technologies targeting legacy oceanic plastic pollution hotspots with highest ecological risks on short and long timescales, such as coastal and marginal seas and subtropical oceanic gyres [54, 70]. Besides removing plastic, cleanup activities also monitor and measure the plastic pollution problem. Data and knowledge on the scale of the plastic problem over time as a result of cleanup activities will allow the effectiveness of upstream, midstream and downstream measures of the Global Plastics Treaty to be assessed.

The strong connectivity between ocean regions makes plastic pollution a global problem since plastic debris can be transported over long distances [71–73]. As a result, plastic pollution has reached even the most remote areas [74–76]. Moreover, some regions receive plastic pollution that originated from other countries [60, 67]. Therefore, dealing with ocean plastic pollution will necessarily involve a debate on global justice and equity in the face of the global plastic pollution problem. Furthermore, offshore plastic accumulation zones are in areas beyond national jurisdiction and therefore without clearly attributable responsibility. This highlights the need for international treaties, such as the treaty on Biodiversity Beyond National Jurisdiction (BBNJ) and the coming Global Plastics Treaty, to solve a multigenerational collective problem, in a collective way.

Conclusions

While uncertainty remains in the quantification of impacts of plastic in the marine environment, preliminary research based on global oceanic models indicates substantial ecological impacts. In the context of multiple anthropogenic threats to the oceans, avoidance of long-term, widespread ecological damage should be a priority and all measures to prevent plastic impacts must be encouraged. We fully support the objectives of the Global Plastics Treaty negotiations and argue that ending the flux of plastics pollution into the environment will be insufficient to stop contamination impacts associated with plastic already present in our oceans. The remaining meetings of the Intergovernmental Negotiating Committee on Plastic Pollution should elevate discussions around the remediation of oceanic plastic pollution and establish clear targets, including accumulation areas beyond national jurisdiction such as the subtropical oceanic gyres. The coming Global Plastics Treaty should formalize how states can collectively address legacy oceanic plastic pollution and provide stable long-term financial and policy support.

Abbreviations

MT Million metric tons
UNEA United Nations Environment Assembly

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Authors' contributions
M.E, C.R. and K.K. designed the study. C.R. prepared Fig. 1. L.L. performed the numerical modelling and prepared Figs. 2 and 3. C.R., K.K. and M. E. wrote the manuscript with contributions from all authors.

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Availability of data and materials
All data needed to evaluate the conclusions in the paper are present in the paper.

Declarations

Competing interests
M.E. and L.L. are employed by The Ocean Cleanup, a non-profit organization aimed at advancing scientific understanding and developing solutions to rid the oceans of plastic, headquartered in Rotterdam. C.R. and K.K. declare no competing interests.

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