https://doi.org/10.1038/s41467-024-53962-3

Mind the fragmentation gap

Karin Kvale, Zhenna Azimrayat Andrews & Matthias Egger

The Global Plastics Treaty presents an opportunity to "end plastic pollution". Legacy plastics will continue to fragment to secondary microplastics for decades, without additional mitigation measures. We identify this flux as a "fragmentation gap", currently overlooked in global policy targets.

In November 2024, the International Negotiating Committee (INC) of the United Nations Environment Assembly will meet to reach consensus on how best to achieve the joint resolution to "end plastic pollution, including in the marine environment"[1]. The Zero Draft of the treaty envisages a comprehensive approach that targets the full life cycle of plastic, from production to disposal, implemented through a combination of international coordination and national plans[2].

Practical approaches to achieving the resolution have been proposed, including the setting of plastics production and waste reduction targets. A number of studies have been released in both the peer reviewed[3–5] and grey literature[6–9] in recent years, outlining possible reduction scenarios that may be both economically palatable and effective at reducing mismanaged plastic waste (Table 1). Overall, these studies indicate that substantial reductions in mismanaged plastic waste generation and subsequent emissions into the environment are possible using tools currently available, provided that ambitious reduction targets are set.

The issue of legacy plastics are considered in[4] and[7]. Through their design of downstream mitigation in their models, they investigated how removal can contribute towards the reduction of legacy plastic existing in the environment. However, these papers do not explicitly consider the state of contamination this legacy plastic imposes on the environment. While the other above assessments generally acknowledge that additional plastic will enter the environment over their reduction scenarios, their focus on the economic and technological feasibility of reduction neglect a critical examination of the environmental implications—are these proposed reduction scenarios ambitious enough to achieve the resolution of "end(ing) plastic pollution", if pollution means not the flow of plastic into the environment, but the contamination of the environment?

Fragmentation of plastic debris into secondary microplastics

Previous idealised box modelling of plastic pollution cessation demonstrates that legacy mismanaged plastic waste will continue to fragment into smaller and smaller secondary microplastics, and these fragments may persist in terrestrial, coastal, oceanic and atmospheric reservoirs for millennia[10]. In the ocean, modelling of plastic pollution emission reduction demonstrated that with stabilisation of pollution fluxes at year 2020 levels, plastic debris can be expected to continue to increase for decades at the ocean surface[11]. An 80% source reduction from 2020 in that framework stabilised, but did not decrease, surface ocean plastic debris quantities by 2040[12]. Because plastic debris fragments into microplastics, the concentration of secondary microplastics at the ocean surface can be expected to continue to increase for decades even with policies that stabilise or reduce the flow of plastic debris into the ocean[10–12].

There are natural processes that can remove these fragmented secondary microplastics from the ocean surface, however these may occur over months to centuries[13], and transfer the contamination into the ocean interior[14,15]. High pressure, low temperatures, darkness and a lack of oxygen all act to inhibit plastic degradation in the deep ocean. As secondary microplastics are expected to continue to contaminate the ocean despite the deceleration of pollution production, the global ocean inventory of microplastics cannot be expected to decrease within the INC's timeframe for ending plastic pollution (provisionally, by 2040[2]) without addressing legacy pollution already accumulated in the environment.

Tackling plastic pollution through reducing the rate of pollution does not address the extensive quantities of legacy plastic pollution, nor does it address the issue of its fragmentation into secondary micro- and nanoplastics. The current discussions of the INC are therefore not addressing the full lifecycle of this pollutant, by overlooking the continued production of secondary microplastics when left accumulated in the environment. The Zero Draft of the treaty contains but a single mention of the need to cooperate on "effective mitigation and remediation measures" for existing plastic pollution[2]. This fragmentation gap in policy writing will inevitably have consequences for the sustained contamination of the land, atmosphere, and ocean[10].

Sustained contamination of microplastics in marine food webs

Plastic pollution is a dispersive and bioavailable contaminant in marine environments. This contamination has well-documented immediate and downstream detrimental effects on both marine biota and human health, contributing towards a multitude of issues including entanglement of sea life, alteration of food web dynamics, degradation of commercial fish quality and quantity, and the translocation of nano-sized plastics into animal (including human) tissues[12]. These threats to environmental and human health have contributed towards the formation of the United Nations Environment Assembly resolution to end plastic pollution.

A new analysis applied idealised microplastic pollution reduction trajectories from 2026 to an Earth system climate model that included representation of microplastics' interactions with the base of the marine food web[14]. The results of this study described that the whole ocean inventory of free-floating microplastic could be stabilised or possibly reduced, and surface concentrations decreased this century if pollution reduction rates of microplastic emitted into the ocean exceed 5% per year. This figure is encouraging in comparison with the technologically feasible, yet ambitious rates of plastic pollution reduction that have been previously proposed (Fig. 1). However, this model did not explicitly account for fragmentation of plastics in the environment.

Table 1 | Description of studies modelling possible pollution reduction scenarios and their predicted outcomes for the state of plastic pollution

Proposed scenario	Predicted results	Downstream mitigation	Source
Global system change for waste management: "all feasible interventions"	A 78% reduction of plastic pollution, relative to a BAU scenario at 2040	Not present	3
Extraordinary global efforts resulting in reductions of plastic waste generation; and environmental recovery of plastic pollution	A reduction of plastic waste generation rate to 8Mt per year by 2030	Present	4
Significant investments into waste management infrastructures relative to countries' Gross Domestic Product growth and reduced use of plastic	Decreasing rates of mismanaged plastic waste production rates to one third of 2019's value by 2060	Not present	5
Global system change for waste management using existing technologies	An 80% reduction in marine plastic pollution rates, relative to a BAU scenario at 2040	Not present	6
Global system change through three market shifts: reuse, recycle, and reorient and diversify (the plastic market)	An 80% reduction of plastic pollution rates, relative to BAU scenario at 2040	Not present	8
Global Rules Scenario: common global policy interventions implemented across the plastic lifecycle	A 90% reductio in mismanaged plastic waste by 2040, relative to 2019 rates	Present	7
Global Ambition Scenario: reductions in plastic use and waste predominately through taxation	An 85% reduction of plastic waste generation relative to a BAU scenario at 2060	Not present	9

BAU stands for business-as-usual, or current trends in plastic production and waste management behaviour continuing into the future.

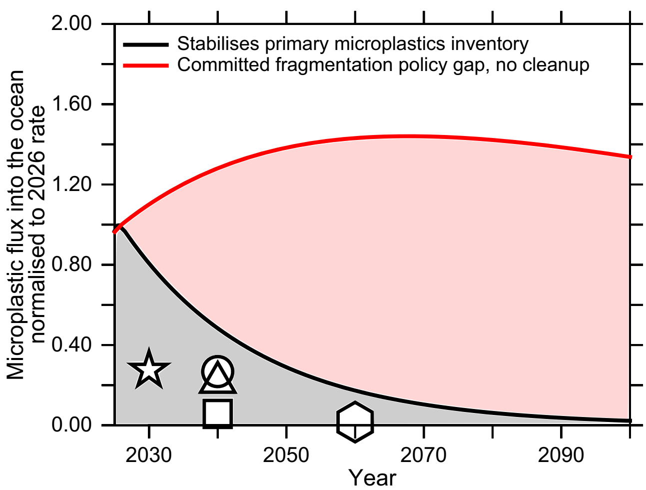

Fig. 1 | The fragmentation policy gap. Published plastics pollution reduction scenarios based on economic or technological constraints (circle[3], star[4], triangle[6], square[7], hexagon[9]). A 5% per annum or greater reduction in microplastics pollution flux to the ocean from 2026 was found to successfully stabilise ocean contamination this century[14] (grey shaded region). If it is assumed that the plastics pollution reduction scenarios result in equivalent reductions in microplastics flux, ocean primary microplastics contamination stabilisation is economically palatable and technologically achievable. However, stronger measures that include active debris removal will be required to achieve reductions in fluxes if legacy debris fragmentation to secondary microplastics is considered. The pink shaded region illustrates the committed fragmentation policy gap; the flux of fragmenting legacy discarded waste at 2026 calculated using the box model of[10]. To facilitate comparison between scenarios with different baseline assumptions, all are presented as reduction relative to the business-as-usual scenario at year 2026 from[14].

The study[14] also found that as microplastics interact with and are transported throughout the biological plastic sink, they can be expected to continue to contaminate the water column over a millennial time scale. Theoretically these microplastics then maintain moderate to high levels of contamination in the food web, despite potential reductions in the quantities of free-floating microplastics due to policy intervention targeting reducing microplastic fluxes to the ocean. Considering then the risk of fragmentation from existing pollution, microplastic being bioavailable can be expected to be an issue for centuries to millennia. While risks of contamination remain poorly understood, modelling has demonstrated potential impacts from microplastics on food web structure, nutrient, oxygen, and carbon cycles.

Downstream measures to mitigate the severity of contamination

The abovementioned studies recognise that microplastics can be expected to be a geographically ubiquitous and persistent pollutant in marine environments and marine biology, despite upstream interventions to reduce pollution rates. However, the retention of microplastic in biology is strongly dependent on the total input[14]. This indicates that early and aggressive mitigation of plastic pollution could reap long-lasting benefits for ocean food webs. By preventing existing plastic from continuing to fragment, the total contamination potential of secondary microplastics would be reduced[10]. Aggressive clean-up of legacy plastic debris pollution at a rate of 3% per year in combination with the waste reduction scenario of ref. 3 stabilises the flux of secondary microplastics into the surface ocean by the year 2050, and reduces the flux of secondary microplastics to the ocean by 11% in the year 2050 relative to upstream measures alone[10]. This result was found in a box model that explicitly accounted for possible natural removal of microplastics including by beaching and sedimentary deposition[10]. The INC should consider the future exposure of food webs, including in the marine environment, to microplastics, and therefore also prioritise mitigation and reduction efforts which target existing pollution to minimise this pollution-fragmentation gap.

Clean-up as an "equal pillar" of the global plastics treaty

Existing technologies have the potential to contribute towards the INC's aim of ending plastic pollution, if policies are implemented effectively. However, current policy discussions have not addressed the extent of the risks to food webs and human health of long-term and pervasive secondary microplastic contamination of the environment. Upstream techniques to reduce the rate of pollution production will not ease the pressures that marine food webs will be facing, due to their ability to retain contamination and ongoing fragmentation of legacy plastic pollution, which we identify as "the fragmentation gap" currently overlooked in INC negotiations. The long-term state of contamination for marine biology particularly would benefit from both a deceleration in the production of pollution and the effective removal of existing plastics through the implementation of environmentally and socially sound clean-ups, which should be codified as an "equal pillar" into the Global Plastics Treaty.

Data availability

Model code and data from Azimrayat Andrews, et al.[14] can be found at https://zenodo.org/records/10484922, https://doi.org/10.5281/zenodo.10484921. Model outputs from the box model of Sonke et al.[10], as well as the figure plotting script used to create Fig. 1, can be found at https://doi.org/10.5281/zenodo.12703009.

Karin Kvale [1,2] ✉, **Zhenna Azimrayat Andrews** [3] & **Matthias Egger** [4,5]

[1]GNS Science, 1 Fairway Ave., 5010 Lower Hutt, New Zealand. [2]Aotearoa Blue Ocean Research, 325A Muritai Road, 5013 Lower Hutt, New Zealand. [3]University of Cambridge, Cambridge, UK. [4]The Ocean Cleanup, Coolsingel 6, 3011 AD Rotterdam, The Netherlands. [5]Egger Research and Consulting, Ullmannstrasse 13a, 9014 St, Gallen, Switzerland. ✉e-mail: aotearoablueocean@gmail.com

Received: 28 July 2024; Accepted: 22 October 2024;
Published online: 13 November 2024

References

1. United Nations Environment Assembly of the United Nations Environment Programme. 5/14. End plastic pollution: towards an international legally binding instrument. (2022).
2. *Zero Draft Text of the International Legally Binding Instrument on Plastic Pollution, Including in the Marine Environment*. https://www.unep.org/inc-plastic-pollution/session-3/documents#WorkingDocuments (2023).
3. Lau, W. W. Y. et al. Evaluating scenarios toward zero plastic pollution. *Science* **369**, 1455–1461 (2020).
4. Borrelle, S. B. et al. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science* **369**, 1515–1518 (2020).
5. Lebreton, L. & Andrady, A. Future scenarios of global plastic waste generation and disposal. *Palgrave Commun.* **5**, 6 (2019).
6. Systemiq. *Breaking the Plastic Wave*. https://www.systemiq.earth/breakingtheplasticwave/ (2020).
7. Systemiq. *Towards Ending Plastic Pollution by 2040*. https://pub.norden.org/temanord2023-539/ (2023).
8. United Nations Environment Programme. *Turning off the Tap*. https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy (2023).
9. OECD. *Global Plastics Outlook*. https://doi.org/10.1787/aa1edf33-en (2022).
10. Sonke, J. E. et al. A mass budget and box model of global plastics cycling, degradation and dispersal in the land-ocean-atmosphere system. *Microplastics Nanoplastics* **2**, 28 (2022).
11. Lebreton, L., Egger, M. & Slat, B. A global mass budget for positively buoyant macroplastic debris in the ocean. *Sci. Rep.* **9**, 12922 (2019).
12. Richon, C., Kvale, K., Lebreton, L. & Egger, M. Legacy oceanic plastic pollution must be addressed to mitigate possible long-term ecological impacts. *Microplastics Nanoplastics* **3**, 25 (2023).
13. Zhu, L., Zhao, S., Bittar, T. B., Stubbins, A. & Li, D. Photochemical dissolution of buoyant microplastics to dissolved organic carbon: Rates and microbial impacts. *J. Hazard. Mater.* **383**, 121065 (2020).
14. Azimrayat Andrews, Z., Karin, K. & Hunt, Claire Slow biological microplastics removal under ocean pollution phase-out trajectories. *Environ. Res. Lett.* **19**, 064029 (2024).
15. Egger, M., Sulu-Gambari, F. & Lebreton, L. First evidence of plastic fallout from the North Pacific Garbage Patch. *Sci. Rep.* **10**, 7495 (2020).

Acknowledgements

M.E. acknowledges funding from the donors of The Ocean Cleanup. K.K. acknowledges support from the New Zealand Ministry of Business, Innovation and Employment within the Antarctic Science Platform, grant ANTA1801. K.K. also acknowledges support from the New Zealand Ministry of Business, Innovation and Employment through the Global Change through Time programme (Strategic Science Investment Fund, contract C05X1702).

Author contributions

K.K., Z.A.A., and M.E. conceptualised and wrote the manuscript. K.K. and Z.A.A. were responsible for the methodology, investigation, and visualisation.

Competing interests

M.E. is employed by The Ocean Cleanup, a non-profit organisation aimed at advancing scientific understanding and developing solutions to rid the ocean of plastic, headquartered in Rotterdam.

Additional information

Correspondence and requests for materials should be addressed to Karin Kvale.