PLASTIC POLLUTION

Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution

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Plastic pollution is a planetary threat, affecting nearly every marine and freshwater ecosystem globally. In response, multilevel mitigation strategies are being adopted but with a lack of quantitative assessment of how such strategies reduce plastic emissions. We assessed the impact of three broad management strategies, plastic waste reduction, waste management, and environmental recovery, at different levels of effort to estimate plastic emissions to 2030 for 173 countries. We estimate that 19 to 23 million metric tons, or 11%, of plastic waste generated globally in 2016 entered aquatic ecosystems. Considering the ambitious commitments currently set by governments, annual emissions may reach up to 53 million metric tons per year by 2030. To reduce emissions to a level well below this prediction, extraordinary efforts to transform the global plastics economy are needed.

Countries around the world are struggling to manage current volumes of plastic waste and ubiquitous plastic pollution (*1*, *2*). From the poles to the deep ocean basins, marine and freshwater ecosystems are accumulating the world's plastic debris (*3*–*5*). Simultaneously, the petrochemical industry announced over $204 billion U.S. in investment driven by the shale gas boom, leading to a projected acceleration in virgin plastic production (*6*).

As plastic production surges, multiscale commitments aim to reduce plastic emissions into the environment [e.g., Addressing Single-Use Plastic Products Pollution (Resolution EA.4/L9) (*7*), the United Nations Environment Assembly Resolutions Marine Litter and Microplastics (*1*), and Goal 14.1 of the United Nations Sustainable Development Goals (*8*)]. Communities, nongovernmental organizations (NGOs), and businesses are cleaning beaches and promoting zero-waste lifestyles (*9*). Governments are banning and placing levies on single-use consumer plastic products and, with the private sector, investing in plastic waste management including integration into a circular economy (*10*–*12*). A recent amendment to the Basel Convention targets marine plastic pollution by tracking the global trade of plastic waste to address issues of oversupply to countries that lack the capacity to manage it (*13*). However, all commitments to date lack a quantitative model that connects these actions to a measurable reduction in plastic emissions.

Here, we present a mechanistic model to evaluate how different levels of effort would reduce plastic emissions into the world's freshwater and marine ecosystems, which includes major rivers, lakes, and oceans (hereafter referred to simply as "aquatic ecosystems"), by 2030. For 173 countries, representing ~97% of the world's population, we estimate the amount of inadequately managed plastic waste entering aquatic ecosystems annually from 2016 to 2030 for three scenarios: business as usual (BAU), in which plastic production and waste generation follow current trajectories; an ambitious scenario that draws upon existing global commitments to reduce plastic emissions (*1*, *9*, *10*, *14*, *15*); and a target scenario to reduce annual plastic emissions. Because an environmentally acceptable threshold has yet to be defined, we set the target scenario to 8 million metric tons (Mt), the estimated global emissions in 2010 to the oceans [(*16*); a subset of aquatic ecosystems considered here] that galvanized global action on plastic pollution by a variety of stakeholders (*7*). Scenarios demonstrating the level of effort required to achieve lower targets can be found in the supplementary materials.

We can predict plastic emissions entering aquatic ecosystems to 2030 by integrating expected population growth (*17*), annual waste generation per capita (*2*), the proportion of plastic in waste [(*2*); incorporating an increase in plastic materials associated with predicted production increases], and the proportion of inadequately managed waste by country [(*2*, *16*, *18*); see the supplementary materials; fig. S1]. For 173 countries with available data, we calculated annual plastic emissions entering aquatic ecosystems using a distance-based probability function. This function estimates the proportion of inadequately managed waste to reach the nearest aquatic ecosystem based on spatially explicit waste generation and downhill flow accumulation [(*18*, *19*); see the supplementary materials; figs. S1 and S2]. That is, the closer to an aquatic ecosystem that waste is generated and inadequately managed, the greater the probability it will enter that aquatic ecosystem.

To account for the differences in plastic waste generation rates and waste management infrastructure among economies [(*2*); Table 1; see the supplementary materials], we adjusted variables for each country based upon their socioeconomic status as defined by the World Bank (*17*): high income (HI), upper-middle income (UMI), lower-middle income (LMI), and low income (LI). Across the three scenarios, we modeled three types of mitigation strategies over time: reducing waste generation (e.g., bans on single-use plastics), improving waste management (capture and containment of plastic waste), and environmental recovery (e.g., clean-up). A list of example actions that could be taken to achieve each type of strategy can be found in the supplementary materials (table S2). We use a Monte Carlo simulation to propagate uncertainty of input parameters and scenarios (see the supplementary materials).

We estimate that ~19 to 23 Mt, or 11%, of plastic waste generated globally in 2016 entered aquatic ecosystems (Fig. 1 and table S4; see the supplementary materials). This is consistent with an estimate of annual river emissions to the global oceans [0.8 to 2.7 Mt (*20*)]

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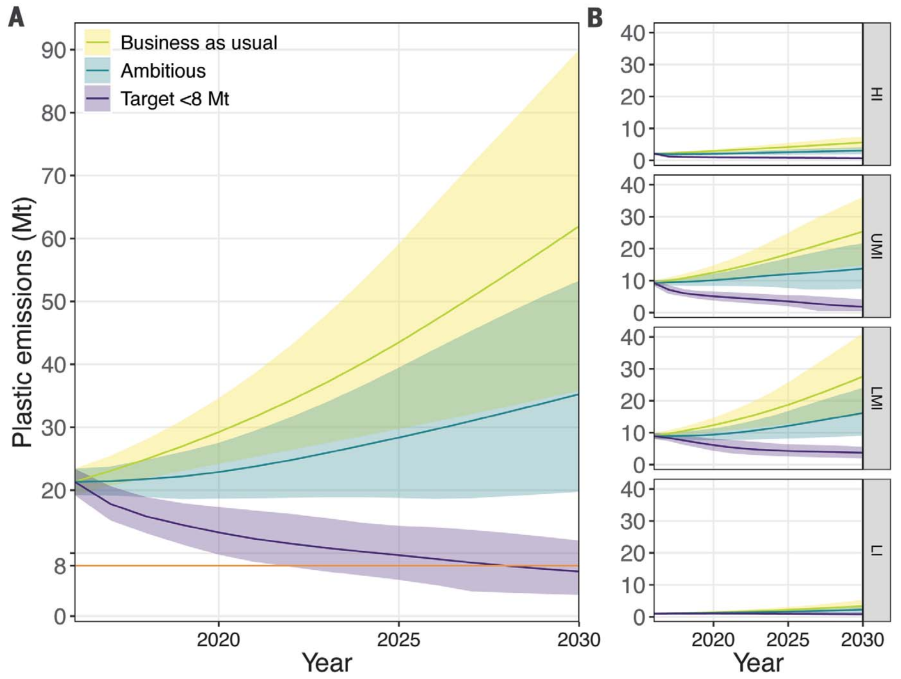

Fig. 1. Annual global plastic emissions into aquatic ecosystems. Data include major rivers, lakes, and the oceans in million metric tons (Mt) from 2016 to 2030 (**A**) and for each income status (**B**) as defined by the World Bank (*17*) showing the BAU (yellow), ambitious (blue), and target <8 Mt (purple) scenarios. Shaded areas represent 80% credible intervals indicating the uncertainty in plastic waste generation and the scenario implementation into the future. Orange horizontal line represents the target of <8 Mt, which is a frequently cited statistic in global policy discussions as an unacceptable amount of plastic emissions to the marine ecosystem alone (a subset of the aquatic ecosystems considered here) (*7*).

that is calibrated with field observations. Our estimate is larger because it includes the amount that accumulates in lakes and rivers in addition to the plastic that escapes to the ocean. Under BAU, we predict that the amount of plastic waste entering the world's aquatic ecosystems could reach 90 Mt/year by 2030 if waste generation trends continue as expected with no improvements in waste management (Fig. 1A and table S4; see the supplementary materials).

Under the ambitious scenario, we predict between 20 and 53 Mt/year of plastic emissions to aquatic ecosystems by 2030, remaining at or exceeding 2016 levels despite tremendous reduction efforts by the global community (Fig. 1A, Table 1, and table S4; see the supplementary materials). The ambitious scenario to reduce plastic emissions is informed by global commitments from the G7 Plastics Charter, the European Union Strategy, the United Nations Environment Programme, Clean Seas, and the Our Oceans conferences. Because these commitments generally lack specific numerical targets and not all countries have made commitments, we apply reduction targets to all countries within an income status based upon existing commitments made by individual countries (see the supplementary materials). The ambitious scenario includes: (i) plastic waste generation reduced from predicted trends by 10% in HI, 5% in UMI, 5% in LMI, and no change from 2016 in LI countries; (ii) an increase in the proportion of managed waste, where HI countries reach a minimum of 90% managed waste (compared with a 2016 mean of 63%), UMI countries reach 70% (2016 mean of 40%), LMI countries reach 50% (2016 mean of 21%), and LI countries reach 30% (2016 mean of 6%); and (iii) recovery of annual global plastic emissions from aquatic environments of up to 10% by 2030 in all countries [Table 1; see the supplementary materials (*21*)].

For the third scenario, we used our model to estimate the effort necessary to achieve a specified plastic emissions target by 2030 (<8 Mt/year). We first focused on each intervention strategy (plastic reduction, waste management, and environmental recovery) independently while holding the others at the ambitious scenario levels. If additional actions were to solely focus on reduction, then plastic waste generation would need to be reduced by 85% across all income levels. If additional actions were to solely focus on waste management, then every country would have to make exceptional efforts to properly manage ≥99% of its plastic waste. If additional actions were to solely focus on recovery, then 85% of annual global emissions would have to be recovered from the environment by 2030 (table S3; see the supplementary materials). Although many stakeholders heavily promote only one of these strategies as the "best one," these results demonstrate that drastic reductions in future plastic emissions cannot be achieved with any one strategy independently (Table 1).

Next, we systematically increased the level of effort for all three strategies simultaneously until the target was reached in 2030 (mean global emissions of <8 Mt; Fig. 1A, fig. S3, and table S3; see the supplementary materials). This requires plastic waste generation to be reduced by 40% in HI, 35% in UMI and LMI, and 25% in LI countries compared with the BAU trajectory. Levels of managed waste must reach 99% in HI and UMI countries, 80% in LMI countries, and 60% in LI countries. Recovery of 40% of annual global emissions by 2030 is needed (Fig. 1A and Table 1). Considering all three strategies combined, the effort required to meet a reduction target of even 8 Mt far exceeds the existing and highly ambitious commitments to date from governments, industries, NGOs, and communities combined (e.g., *1, 9, 10, 14, 15*).

It is important to note that these values may be an underestimate of plastic emissions. Across all scenarios, UMI and LMI countries contribute the most plastic waste emissions compared with HI and LI countries (Fig. 1B and Table 1; see the supplementary materials, appendix 3). However, the trade of plastic waste was not accounted for in the current model (see the supplementary materials). Waste shipped predominantly from HI to UMI, LMI, and LI countries for processing may enter into a country with no formal waste management system or one that is less tractable, therefore misrepresenting HI countries' contributions to plastic emissions (*22*). Other factors may also lead to uncertainties in our results. Global scale data for plastic waste generation, collection, and disposal are often lacking or unreliable because of inconsistencies in reporting among countries, differences in methodologies and units used in reporting, and omitted values (*2*, *18*). We do not include primary microplastics, microplastics produced from the wear of products still in use, or microplastics entering the environment through wastewater, although these are likely comparatively small in mass. We also do not include abandoned, lost, or discarded fishing gear, which is an important source of plastic waste, especially in marine

Table 1. Mitigation strategy scenario values and projections of 2030 plastic emissions. Shown are income status and global plastic emissions in 2030 and the levels of plastic waste reduction, waste management improvement, and recovery of plastic waste under BAU, ambitious, and target (<8 Mt) scenarios. Specific actions that can be taken to achieve reductions in plastic waste generation (e.g., product bans or taxes), waste management improvement (e.g., increased collection and controlled landfill), and recovery (e.g., beach clean-ups) can be found in table S2. In the ambitious and target scenarios, changes in plastic waste generation are reductions implemented over time and fully achieved by 2030 and to the same level by countries in the same income status as defined by the World Bank (*17*). "No change" indicates that 2016 proportions of inadequately managed plastic remain at 2016 values.

	Change in plastic waste generation from predicted growth to 2030, % per capita		Managed waste levels by 2030, %		Recovery by 2030, % of global annual emissions	2030 Income status emissions (Mt), 80% credible interval		2030 Global plastic emissions (Mt), 80% credible interval
Business as usual	Country-level projections based on predicted trends		HI:	No change	All: 0	HI:	3.6–7.4	35.8–90.0
			UMI:	No change		UMI:	14.8–36.1	
			LMI:	No change		LMI:	15.6–41.1	
			LI:	No change		LI:	1.9–5.3	
Ambitious	HI:	–10	HI:	90	All: 10	HI:	1.9–4.1	19.8–53.3
	UMI:	–5	UMI:	70		UMI:	7.5–21.6	
	LMI:	–5	LMI:	50		LMI:	9.1–24.1	
	LI:	0	LI:	30		LI:	1.2–3.5	
Target (<8 Mt)	HI:	–40	HI:	99	All: 40	HI:	0.5–0.9	3.4–12.0
	UMI:	–35	UMI:	99		UMI:	0.5–4.1	
	LMI:	–35	LMI:	80		LMI:	2.0–5.6	
	LI:	–25	LI:	60		LI:	0.4- 1.4	

ecosystems (*23*), or the unregulated burning of inadequately managed plastic waste, which may decrease plastic emissions. Finally, there is a lack of data for most countries representing the efficacy of the informal waste management sector (*2*). One study in India estimated that 50 to 80% of generated plastic waste is recovered by the informal sectors (garbage collectors, waste pickers, and waste dealers) and is thus kept out of the environment [(*24*); see the supplementary materials]. The creation of a long-term standardized global monitoring program and open-access data for plastics placed on the market, waste generation and management, the international trade of waste, environmental emissions, and transport in the environment will improve our ability to quantify both plastic emission pathways and the efficacy of mitigation strategies.

Our results show that the efforts required to meaningfully reduce plastic emissions by 2030 are extraordinary (Fig. 1 and Table 1). Increased waste management capacity alone cannot keep pace with projected growth in plastic waste generation. Further, without major technological innovation, it is inconceivable that efforts to recover plastic waste from the environment could reach even 10% of annual emissions (~2.4 to 6 Mt in 2030), whereas our model shows that 40% recovery is required to reduce emissions to <8 Mt (Table 1). These findings emphasize that unless growth in plastic production and use is halted, a fundamental transformation of the plastic economy to a circular framework is essential, where end-of-life plastic products are valued rather than becoming waste.

Increasing global efforts to manage plastic waste must consider plastic pollution as a multidimensional issue. This includes evaluating the financial and social costs of implementing (or not implementing) mitigation strategies and also the impacts of different mitigation strategies on economies, social justice, and human and environmental health to achieve global sustainable development goals. For example, waste-to-energy processing (i.e., incineration) reduces plastic waste volumes but may cause human health impacts from hazardous byproducts, create social justice issues, and increase greenhouse gas emissions (*25*, *26*). Without such considerations, we risk creating perverse outcomes from the transformational shifts needed to address plastic pollution.

Plastic pollution is a burgeoning threat to the sustainability of our planet (*7*, *8*, *27*). The world is responding at an already impressive scale, with grassroots action, national-level product bans, public-private partnerships for investment in waste management infrastructure, innovative alternatives to leakage-prone plastic products, and greater transparency in the trade of plastic waste (*7*, *10*, *13*). Still, our results show that achieving substantial reductions in global plastic emissions to the environment requires an urgent transformative change. Key policies to achieve such a transition include reducing or eliminating the use of unnecessary plastics, setting global limits for virgin plastic production, creating globally aligned standards for commodity plastics to be practically recoverable and recyclable by design, and developing and scaling plastic processing and recycling technologies. Such harmonized policies can enable plastics to remain a valuable and useful commodity (*10*, *12*). Further, some plastics will inevitably be emitted to the environment. Thus, recovery of plastic waste has to be a sustained priority to minimize adverse impacts on species and ecosystems (*28*) and to limit harmful waste management practices such as open burning (*25*). Without this transformation, we risk continuing to invest large amounts of human capital and financial resources with little to no hope of reducing plastic pollution in the world's rivers, lakes, and oceans.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs S1 to S5
Tables S1 to S4
References (*29*–*35*)

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A mess of plastic

It is not clear what strategies will be most effective in mitigating harm from the global problem of plastic pollution. Borrelle *et al.* and Lau *et al.* discuss possible solutions and their impacts. Both groups found that substantial reductions in plastic-waste generation can be made in the coming decades with immediate, concerted, and vigorous action, but even in the best case scenario, huge quantities of plastic will still accumulate in the environment.

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