PLASTIC POLLUTION

Evaluating scenarios toward zero plastic pollution

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Plastic pollution is a pervasive and growing problem. To estimate the effectiveness of interventions to reduce plastic pollution, we modeled stocks and flows of municipal solid waste and four sources of microplastics through the global plastic system for five scenarios between 2016 and 2040. Implementing all feasible interventions reduced plastic pollution by 40% from 2016 rates and 78% relative to "business as usual" in 2040. Even with immediate and concerted action, 710 million metric tons of plastic waste cumulatively entered aquatic and terrestrial ecosystems. To avoid a massive build-up of plastic in the environment, coordinated global action is urgently needed to reduce plastic consumption; increase rates of reuse, waste collection, and recycling; expand safe disposal systems; and accelerate innovation in the plastic value chain.

Plastic pollution is globally ubiquitous. It is found throughout the oceans, in lakes and rivers, in soils and sediments, in the atmosphere, and in animal biomass. This proliferation has been driven by rapid growth in plastic production and use combined with linear economic models that ignore the externalities of waste (*1*, *2*). A sharp rise in single-use plastic consumption and an expanding "throw-away" culture (*1*) have exacerbated the problem. Waste management systems do not have sufficient capacity at the global level to safely dispose of or recycle waste plastic (*3*, *4*), resulting in an inevitable increase in plastic pollution into the environment. Previous studies estimated that ~8 million metric tons (Mt) of macroplastic (*5*) and 1.5 Mt of primary microplastic (*6*) enter the ocean annually. Comparable estimates for terrestrial plastic pollution have yet to be quantified. If plastic production and waste generation continue to grow at current rates, the annual mass of mismanaged waste has been projected to more than double by 2050 (*1*, *2*), and the cumulative mass of ocean plastic could increase by an order of magnitude from 2010 levels by 2025 (*5*). Despite the magnitude of these flows, the efficacy and economic costs of solutions proposed to solve the plastic waste problem—the uncontrolled release of plastic waste into the environment resulting from ineffective management—remain unknown.

A growing body of evidence points to a broad range of detrimental effects of plastic pollution. Nearly 700 marine species and more than 50 freshwater species are known to have ingested or become entangled in macroplastic (*7*, *8*), and there is growing evidence that plastic is ingested by a wide range of terrestrial organisms (*9*). Plastic pollution affects many aspects of human well-being: affecting the aesthetics of beaches (*10*), blocking drainage and wastewater engineering systems (*11*), and providing a breeding ground for disease vectors (*10*, *12*). The lower-bound estimate of the economic impact on costs of plastic pollution to fishing, tourism, and shipping have been estimated at $13 billion annually (*13*). Although harmful effects of microplastic (here defined as plastics <5 mm) have not been consistently demonstrated, ingestion has been documented across trophic levels and at all depths of the ocean, in individual organisms and species assemblages (*8*, *14*) and in terrestrial organisms (*15*). Microplastics are also increasingly found in the human food system, although their impacts on human health are difficult to assert and require further research (*16*, *17*). Plastic production, collection, and disposal are also major sources of greenhouse gas (GHG) emissions (*18*).

Cost-effective solutions to managing plastic waste vary considerably across geographies and social settings (*3*), and a variety of solutions to the plastic pollution problem have been proposed at local, national, and regional levels (*19*, *20*). Some proposed interventions focus on postconsumption management, requiring considerable growth in investment and capacity of waste management solutions (*21*, *22*). Other interventions prioritize reducing plastic through replacement with alternative products, reuse, and the development of new delivery models (*23*). Individual countries have established bans or levies on select plastic products, with a particular focus on banning single-use carrier bags and microbeads in cosmetic products (*24*, *25*). The European Union recently adopted a directive on single-use plastics (*26*), and the Basel Convention was amended to regulate the international trade of plastic waste (*27*). The scientific community and nongovernmental organizations are also working to identify solutions (*21*, *28*). Despite these efforts, a global evidence-based strategy that includes practical and measurable interventions aimed at reducing plastic pollution does not yet exist.

Modeling approach

Designing an effective global strategy requires an understanding of the mitigation potential of different solutions and the magnitude of global effort needed to appreciably reduce plastic pollution. To estimate mitigation potential under different intervention scenarios, we developed the Plastics-to-Ocean (P_2O) model. P_2O is a data-driven coupled ordinary differential equation (ODE) model that calculates the flow of plastics through representative systems. We used the model to characterize key stocks and flows for land-based sources of plastic pollution across the entire value chain for municipal solid waste (MSW) macroplastics (figs. S1 and S2) and four sources of primary microplastics (those entering the environment as microplastics) [supplementary materials (SM) section 15 and figs. S3 to S6]. Crucially, it provides estimates of plastic waste input into the environment. Costs are calculated as a function of modeled plastic flows, and changes in costs due to production scale and technological advancement are accounted for through learning curves and returns to scale (SM section 16.1).

We calculated projected growth in demand for plastic using country-level population size (*29*), per capita macroplastic MSW (*30*, *31*), and microplastic-generating product use and loss rates. Per capita waste generation and waste management processes (such as collection costs, collection and processing rates, and recycling recovery value) and rates of primary microplastic generation vary by geography and plastic

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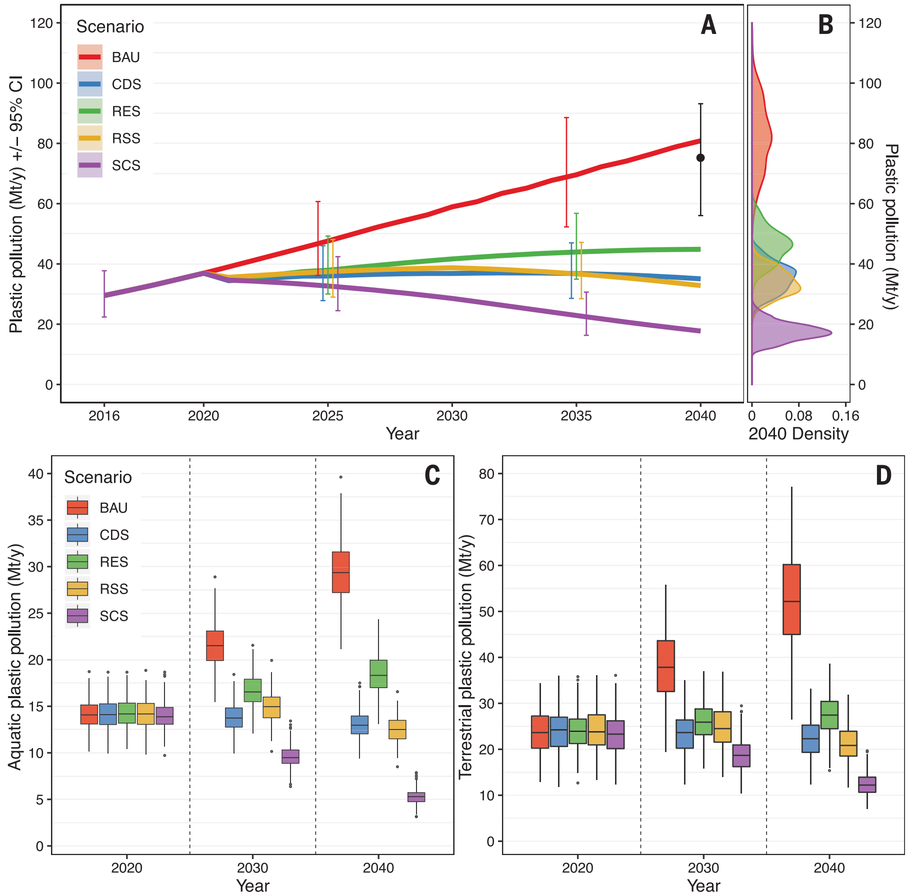

Fig. 1. Annual rates of plastic pollution entering the environment estimated from 300 Monte Carlo simulations. (**A**) Time series of plastic pollution entering aquatic and terrestrial ecosystems (million metric tons/year ± 95% CI) by scenario, 2016 to 2040. Scenarios are Business as Usual (BAU), Collect and Dispose scenario (CDS), Recycling scenario (RES), Reduce and Substitute scenario (RSS), and System Change scenario (SCS). Plastic pollution rates for all scenarios between 2016 and 2020 are identical. The black point estimate in 2040 represents the annual rate of plastic pollution assuming that global commitments to reduce plastic use and increase recycling announced before June 2019 are implemented before 2040. A time series for this scenario is not presented because timelines for implementation are unknown. (**B**) Kernel density estimates for plastic pollution (million metric tons) in 2040 by scenario. (**C** and **D**) Boxplots of plastic pollution entering (C) aquatic and (D) terrestrial ecosystems by scenario for beginning, middle, and end years of scenario implementation. Boxplots follow the Tukey convention: Hinges indicate first and third quartiles; whiskers indicate the most extreme value no further than 1.5 times the interquartile range from the hinge; and horizontal lines indicates the median.

Table 1. Summary statistics and comparison of end-of-life fates for MSW plastic under BAU and SCS. Shown from left to right are plastic mass, percent of total plastic demand under different end-of-life fates for year 2016 and for year 2040 under the Business as Usual (BAU) and System Change scenarios (SCS), and percent change in plastic mass, under different end-of-life fates for SCS in 2040 relative to 2016 and BAU in 2040. Values in square brackets represent the lower and upper bounds of the 95% CI for the values above them. Dashes indicate undefined values whose calculation involves division by zero.

End-of-life fate	Plastic mass (Mt/year)			Fate as % plastic demand			SCS 2040 % change	
	2016	BAU 2040	SCS 2040	2016	BAU 2040	SCS 2040	2016	BAU 2040
Reduction	0 [0, 0]	0 [0, 0]	130 [110, 150]	0 [0, 0]	0 [0, 0]	31 [28, 33]	–	–
Substitution	0 [0, 0]	0 [0, 0]	71 [62, 81]	0 [0, 0]	0 [0, 0]	17 [15, 18]	–	–
Recycling	31 [26, 32]	55 [46, 63]	84 [75, 93]	14 [12, 15]	13 [11, 15]	20 [18, 21]	170 [140, 200]	54 [46, 61]
Disposal	97 [83, 97]	140 [120, 150]	100 [89, 110]	44 [39, 45]	32 [28, 33]	24 [22, 26]	3.5 [3.3, 3.8]	−26 [−24, −28]
Mismanaged	91 [84, 100]	240 [220, 260]	44 [40, 49]	42 [41, 47]	56 [53, 59]	10 [9.4, 12]	−51 [−48, −54]	−81 [−76, −87]
Open burning*	49 [40, 60]	130 [110, 160]	23 [18, 29]	54 [42, 63]	56 [44, 65]	53 [41, 65]	−53 [−45, −61]	−82 [−70, −95]
Dumpsite*	12 [7.4, 21]	25 [14, 41]	3.2 [1.5, 5.0]	13 [8.2, 22]	11 [5.9, 17]	7.3 [3.3, 11]	−74 [−49, −99]	−87 [−54, −120]
Aquatic pollution*	11 [9.0, 14]	29 [23, 37]	5.3 [3.8, 7.0]	12 [9.8, 14]	12 [9.8, 15]	12 [9.0, 15]	−52 [−43, −60]	−82 [−68, −95]
Terrestrial pollution*	18 [13, 25]	52 [34, 70]	12 [7.8, 18]	20 [13, 27]	22 [14, 29]	28 [18, 39]	−33 [−23, −42]	−76 [−55, −97]

*Components of the mismanaged end-of-life fate. These categories sum to the total for mismanaged waste.

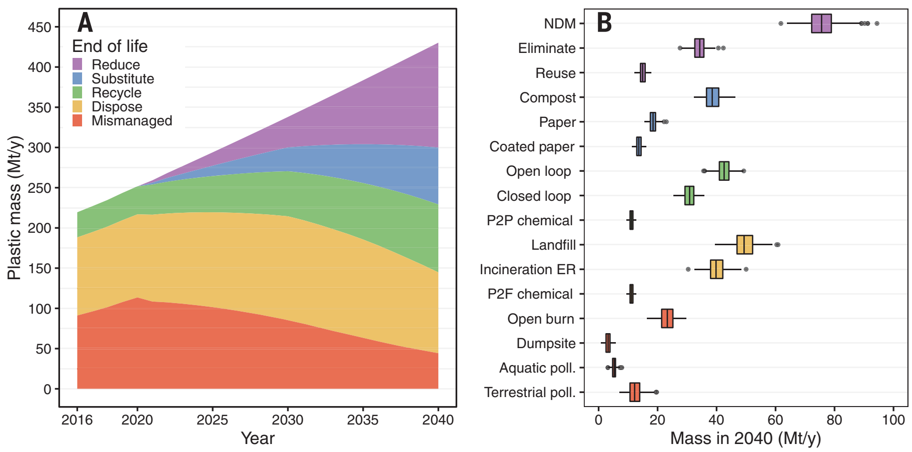

Fig. 2. Fate for all MSW plastic, 2016 to 2040, under the System Change scenario (SCS). (**A**) Annual mass of plastic (million metric tons/year) for each of five end-of-life fates. (**B**) Boxplots showing mass of plastic utility (million metric tons/year) addressed per modeled intervention in 2040, after 20 years of SCS implementation, organized by end-of-life fate. NDM, new delivery model; P2F chemical, plastic-to-fuel chemical conversion; P2P chemical, plastic-to-plastic chemical conversion; Incineration ER, incineration with energy recovery; Aquatic poll., plastic pollution into aquatic systems; Terrestrial poll., plastic pollution into terrestrial systems. Boxplots follow the Tukey convention: Hinges indicate first and third quartiles; whiskers indicate the most extreme value no further than 1.5 times the interquartile range from the hinge; and horizontal lines indicate the median.

category or source (*6*, *32*–*34*). To account for these differences, the global population was split across eight geographic archetypes according to World Bank income categories (low income, lower- and upper- middle income, and high income) and United Nations urban-rural classifications (*29*). Populations were further differentiated by their distance to water (<1 km or >1 km) to estimate their relative flows of plastic pollution to terrestrial versus aquatic (lakes, rivers, and marine environments) systems. To account for different waste management pathways (*35*) and movement rates of waste in the environment (*35*), MSW plastics were differentiated into three material categories: rigid monomaterial, flexible monomaterial, and multimaterial or multilayer. Four microplastic sources were modeled: synthetic textiles, tires, plastic pellets, and personal care products.

Five scenarios were developed to estimate reductions in plastic pollution over the period 2016 to 2040. Scenarios were defined by four high-level classes of interventions (reduce, substitute, recycle, and dispose) and eight system interventions: (i) reducing plastic quantity in the system, (ii) substituting plastics with alternative materials and delivery systems, (iii) implementing design for recycling, (iv) increasing collection capacity, (v) scaling up sorting and mechanical recycling capacity, (vi) scaling up chemical conversion capacity, (vii) reducing postcollection environmental leakage, and (viii) reducing trade in plastic waste (table S7). Scenarios modeled include (i) "Business as Usual" (BAU), (ii) "Collect and Dispose," (iii) "Recycling," (iv) "Reduce and Substitute," and (v) an integrated "System Change" scenario that implemented the entire suite of interventions (tables S8 and S57).

At all relevant geographical scales, waste production and handling data are notoriously difficult to obtain. Many model inputs have a high degree of uncertainty, which was propagated with Monte Carlo sampling. Data inputs and assigned uncertainties are described in SM section 5.6. In the absence of datasets with which to formally validate the model, we conducted sensitivity analyses to quantify the influence of individual model inputs and to identify key drivers of plastic pollution. Model outputs from the BAU scenario were also compared with results from other global studies (*2*, *5*, *36*).

Business as usual

The BAU scenario highlights the scale of the plastic pollution problem and provides a baseline from which to compare alternative intervention strategies (Fig. 1). At a global scale from 2016 to 2040, the annual rate of macro- and microplastic entering aquatic systems from land increased 2.6-fold (Fig. 1C and Table 1). Over the same period, the rate of plastic pollution retained in terrestrial systems increased 2.8-fold (Fig. 1D and Table 1).

When we modeled current commitments to reducing plastic pollution assuming full implementation (SM section 9.1), annual plastic pollution rates into aquatic and terrestrial environments decreased by only 6.6% [95% confidence interval (CI): 5.4, 7.9] and 7.7% [5.2, 10] by 2040, respectively (Fig. 1A) (*37*). This result confirms that current commitments coupled with appropriate policies can reduce plastic waste input into the environment but also shows that considerable additional effort will be needed to match the unprecedented scale of projected environmental plastic pollution.

Plastic pollution rates were found to be particularly sensitive to total plastic mass, collection rates, and the ratio of managed to mismanaged waste. For example, a 1-ton reduction in plastic MSW mass (through reduce and substitute interventions) decreased aquatic plastic pollution by an average of 0.088 tons in low- and middle-income archetypes and an average of 0.0050 tons in high-income archetypes. Across all archetypes, an equivalent increase in the collection of plastic waste (through formal and informal sectors) resulted in an average 0.18-ton decrease in aquatic plastic pollution, whereas a similar decrease in postcollection mismanaged waste produced an average 0.10-ton decrease in aquatic plastic pollution.

Scenarios to reduce plastic pollution

The focus of plastic pollution reduction strategies can be broadly partitioned into upstream (preconsumption, such as reducing demand) and downstream (postconsumption, such as collection and recycling) measures. To parameterize the development of waste management and recycling solutions in the Collect and Dispose, Recycling, and System Change scenarios, we estimated maximum foreseen growth and implementation rates on the basis of historical trends and expert panel consensus assessment (SM section 1). Compared with BAU, the annual combined terrestrial and aquatic plastic pollution rates were reduced by 57% in

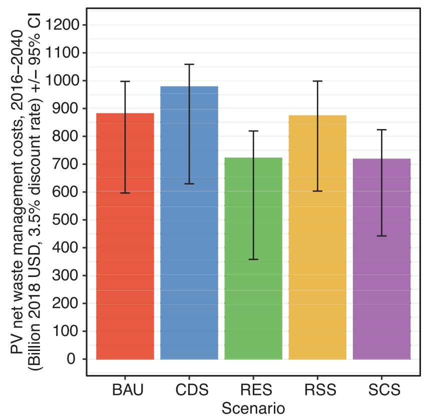

Fig. 3. Present value costs for the management (collection, sorting, recycling, and disposal) of plastic MSW by scenario, 2016 to 2040. Costs (billions 2018 U.S. dollars ± 95% CI) are calculated assuming 3.5% discount rate and are net of revenues associated with the sale of recycled plastic feedstock and electricity generated from plastic incineration with energy recovery. Scenarios are Business as Usual (BAU), Collect and Dispose scenario (CDS), Recycling scenario (RES), Reduce and Substitute scenario (RSS), and System Change scenario (SCS).

2040 [45, 69] under the Collect and Dispose scenario and by 45% [35, 54] under the Recycling scenario (Fig. 1, A and B).

Strategies focused on upstream (preconsumption) solutions were represented by the Reduce and Substitute scenario. We developed a feasibility assessment framework to model the potential development of upstream solutions aimed at reducing the volume of plastics used and disposed of into the waste stream (SM section 9). We assessed 15 major plastic applications against four criteria for technology readiness and unintended consequences related to health and food safety, consumer acceptance (for example, convenience and climate change impacts), and affordability (tables S21 and S22). We assessed the feasibility of substitution with alternative material against the potential for scaling to meaningful levels within the modeling period. Paper, coated paper, and compostable materials met these criteria. Under the Reduce and Substitute scenario, annual combined terrestrial and aquatic plastic pollution in 2040 decreased 59% [47, 72] relative to BAU, whereas annual plastic production decreased by 47% [44, 49]. Consequently, plastic production in 2040 under the Reduce and Substitute scenario (220 Mt/year [200, 240]) was similar to production in 2016 (210 Mt/year [200, 230]).

Neither pre- nor postconsumption interventions alone are sufficient to address the plastic problem. Combining the maximum foreseen application of pre- and postconsumption solutions represents the most aggressive possible solution given current technology: the System Change scenario. In this scenario, annual combined terrestrial and aquatic plastic pollution decreased by 78% [62, 94] relative to BAU in 2040 but only by 40% [31, 48] relative to 2016 pollution rates (Fig. 1, A and B, and Table 1). In 2040, the annual rate of land-based sources of plastic entering aquatic and terrestrial systems decreased by 82% [68, 95] and 76% [55, 97] relative to BAU, respectively (Fig. 1, C and D, and Table 1).

Under the System Change scenario in 2040, a substantial reduction in mismanaged and disposed waste was achieved through increases in the proportion of plastic demand reduced, substituted by alternative materials, and recycled (Fig. 2A and Table 1). These changes to the plastic system resulted in 11% [10, 12] less virgin plastic being produced in 2040 under the System Change scenario than was produced in 2016, and 55% [51, 58] less than in 2040 under BAU. Moreover, this reduction was driven by increases in recycled plastic feedstock, which have lower life-cycle GHG emissions (*18*). Taken together, the System Change scenario moves toward achieving a circular economy in which resources are conserved, waste generation is minimized (*38*), and GHG emissions reduced.

The present value of cumulative, global waste management operations from 2016 to 2040 was approximated to assess the relative cost of each scenario (Fig. 3). Among scenarios, costs varied by less than 20% relative to BAU, were lowest under the System Change and Recycling scenarios, and were highest for the Collect and Dispose scenario. Costs under the System Change scenario were 18% [14, 23] lower than BAU, with increased waste management costs offset by costs savings from reduced plastic production and revenues from recyclate sales, which increased because of product redesign and improved economics of recycling (SM section 16.8). These costs represent only waste management costs, which are generally borne by taxpayers. Corporate engagement, through improved product design, alternative material development, and new business models will be necessary to achieve pollution levels observed in the System Change scenario. This engagement will likely require a substantial shift in private sector investment.

Our results underline the urgency with which extensive interventions are needed. Despite a considerable reduction in annual plastic production and an increase in the proportion of MSW that is effectively managed under the best-case System Change scenario, a substantial amount of plastic waste remained mismanaged (not collected and sorted, recycled, or safely disposed) between 2016 and 2040. When implementation of interventions begins in 2020, the cumulative mass of plastic pollution added between 2016 and 2040 amounts to 250 Mt [190, 310] in aquatic systems (Fig. 4A) and 460 Mt [300, 640] in terrestrial systems (Fig. 4B), which are approximately 1 and 2 times the total annual plastic production in 2016, respectively. If implementation of interventions is delayed

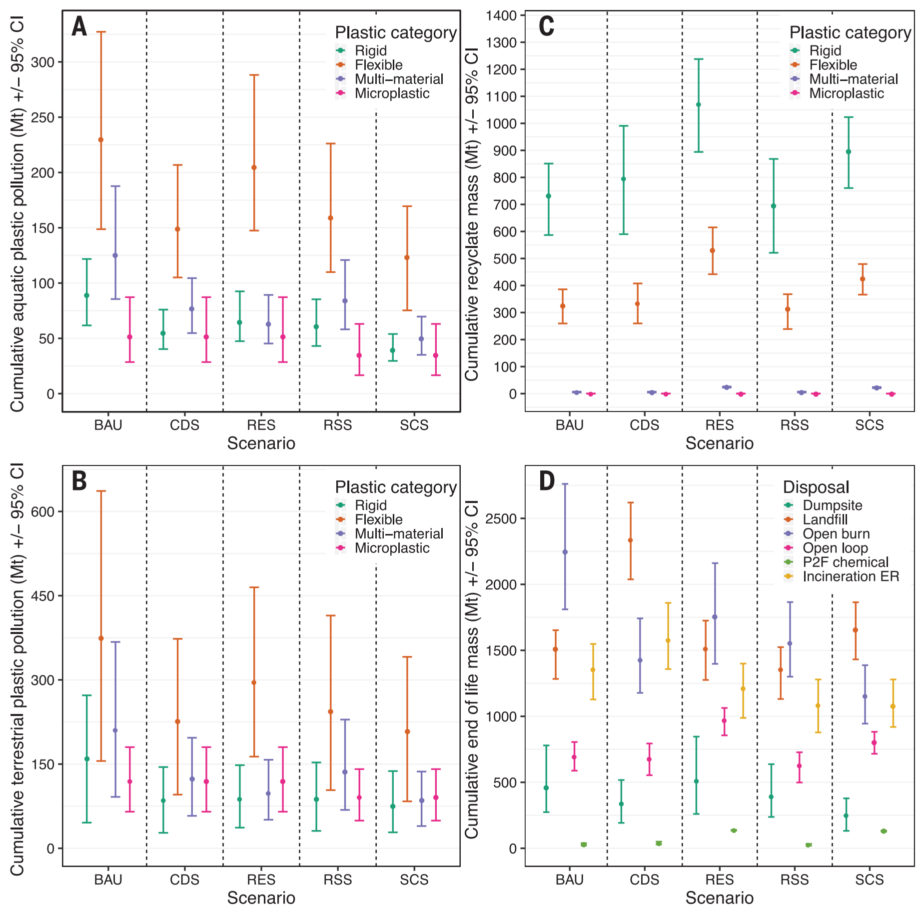

Fig. 4. Cumulative mass of plastic MSW, 2016 to 2040. (**A** and **B**) Cumulative mass of plastic MSW polluting (A) aquatic and (B) terrestrial systems by scenario and plastic type for years 2016 to 2040 (million metric tons ± 95% CI). (**C**) Cumulative mass of plastic MSW recycled for each of four plastic types modeled. (**D**) Cumulative mass of noncircular plastic MSW endpoints, including solutions in the mismanaged (dumpsite or open burning), effectively disposed [landfill, incineration with energy recovery, or plastic-to-fuel (P2F) chemical conversion], and recycling (open loop recycling) categories. Uncertainty bars for P2F chemical conversion are not visible because their endpoints do not exceed the radius of the plotted point estimate. Scenarios are Business as Usual (BAU), Collect and Dispose" scenario (CDS), 'Recycling' scenario (RES), 'Reduce and Substitute' scenario (RSS), and System Change scenario (SCS).

by only 5 years, an additional 300 Mt of mismanaged plastic waste is expected to accumulate in the environment.

Outlook by plastic category

The complex composition of multimaterial plastics limits the technical feasibility of sorting and reprocessing (*39*), decreasing the economic attractiveness of recycling. Accordingly, the annual production of these plastics decreased by 19 Mt [18, 20] from 2016 to 2040 under the System Change scenario, with a shift of similar magnitude to flexible monomaterial plastic production (20 Mt/year [19, 21]).

Because of the relative ease of collection and sorting, recycling was dominated by rigid plastics in all archetypes and across all scenarios (Fig. 4C). Under the System Change scenario in 2040, rigid plastics represented 62% [58, 67] of the annual mass of recycling, with a sizeable component of flexible monomaterial plastic (33% [28, 37]) (Fig. 5A). In comparison, only 5.0% [4.2, 5.4] of recycled material was derived from multimaterial or multilayer waste plastic (Fig. 5A).

The diversity of polymer types, surface contamination, and low density of postconsumer flexible monomaterial limit their capacity for recycling, particularly in geographies where waste collection services are provided by the informal sector. At a global scale, the absolute and relative contribution of flexible monomaterial plastics to environmental pollution grew between 2016 and 2040, from 45% [35, 56] to 56% [40, 73] in aquatic environments and from 37% [18, 52] to 48% [22, 67] in terrestrial environments (Fig. 5, B and C). Accordingly, finding an economically viable solution to effectively manage flexible plastics will be essential for solving the plastic pollution problem.

Similarly, the proportion of total plastic pollution originating from microplastics in the System Change scenario grew from 11% [6.5, 18] to 23% [11, 42] in aquatic systems and from 16% [8.2, 27] to 31% [18, 51] in terrestrial systems over the modeled period (Fig. 5, B and C). Technologies to capture microplastics, which often rely on stormwater and wastewater management and treatment, are rarely economically feasible—even in wealthy regions—because of associated infrastructure costs. This technological challenge is particularly acute for tire particles, which contributed 93% [83, 96] of global microplastic pollution by mass in 2040.

Difficulties to overcome

Scaling collection to all households at a global level is a monumental task that would require connecting over a million additional households to MSW collection services per week from 2020 to 2040; the majority of these unconnected households are in middle-income countries. The effort to increase household waste collection will therefore require a key role for "waste pickers" [the informal collection and recycling sector (*40*)], who link the service chain (MSW collection) to the value chain (recycling) in low- and middle-income settings. Globally, this sector was responsible for 58% [55, 64] of postconsumer plastic waste collected for recycling in 2016. To incentivize the collection of low-value plastics (flexible monomaterial and multimaterial or multilayer plastic) by the informal sector, the profitability of recycling these materials would need to rise to create demand for their collection. Accordingly, investments in collection infrastructure must be coordinated with improved governance around collection, sorting, and safe management of generated waste (*41*).

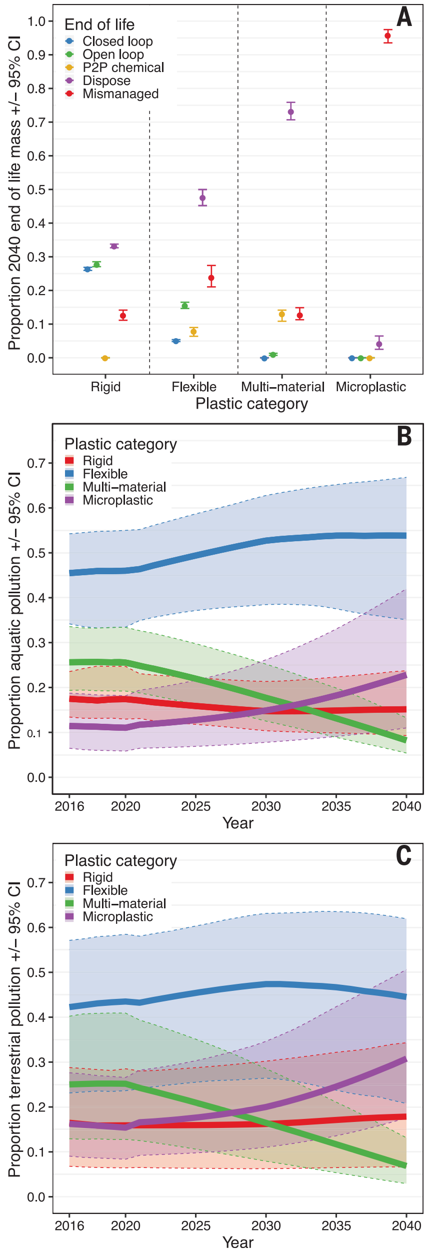

Fig. 5. Fate of plastic MSW by plastic type under the System Change Scenario (SCS). (**A**) Proportion of MSW (± 95% CI) produced in 2040 absorbed by each of three recycling solutions and the dispose and mismanaged end-of-life categories. Even under SCS, few effective solutions are implemented to manage primary microplastics. (**B** and **C**) The proportion of plastic pollution (± 95% CI) entering (B) global aquatic and (C) terrestrial systems by plastic type, 2016 to 2040.

Mismanaged plastic waste (in dumpsites, openly burned, or released into aquatic or terrestrial environments) is associated with a range of risks to human and ecological health (*42*). Substantial quantities of such waste are likely to continue to be emitted into the environment or openly burned through time. Under the System Change scenario, in addition to aquatic and terrestrial pollution, ~250 Mt [130, 380] of waste plastic would accumulate in open dumpsites from 2016 to 2040 and remain a potential source of environmental pollution (Fig. 4D). Many communities in emerging economies with inadequate waste management services and infrastructure burn waste residentially or in open dumpsites without emissions controls. Open burning transfers the pollution burden to air, water, and land through the generation of GHGs, particulate matter (including microplastic particles), and harmful chemicals such as dioxins and other persistent organic pollutants (*43*, *44*). Despite its human health and environmental consequences, open burning was the single largest component of mismanaged plastic waste under all scenarios, with 1200 Mt [940, 1400] of plastic burned in the System Change scenario between 2016 and 2040 (Fig. 4D). It therefore remains a stubborn pollution and social justice problem in need of an effective solution.

Although not strictly mismanaged, the net export of waste from high-income to upper- and lower-middle income countries grew from 2.7 Mt/year [2.4, 4.7] in 2016 to 3.8 Mt/year [0.7, 7.2] in 2040 under BAU. Although a comparatively small amount, these exports have the potential to increase the fraction of mismanaged plastic waste because receiving countries often have insufficient capacity to manage their own waste. Consequently, importing waste for recycling can have the unintended consequence of displacing these developing economies' capacity to recycle their domestic waste (*45*).

Although efforts to measure the amount of plastic pollution entering rivers and oceans have increased in recent years (*46*–*48*), key data gaps remain. To better estimate the effects of consumer, corporate, and policy actions on solving the plastic pollution problem, additional empirical data are needed throughout the plastics system—particularly in developing economies. Moreover, a more complete accounting of the benefits, costs, and externalities of plastic use is needed to design policies that align social and financial incentives and minimize plastic pollution. These data deficiencies currently prevent application of the model at finer geographical scales and limit the granularity of the system representation. In particular, data from the informal sector of the global waste management system are scarce, as are data that shed light on the importance of postcollection MSW mismanagement. Additional quantitative data are also needed to better understand key sources, rates, and pathways for microplastic pollution and for maritime sources of plastic pollution.

Addressing the plastic pollution problem

Our analysis indicates that urgent and coordinated action combining pre- and postconsumption solutions could reverse the increasing trend of environmental plastic pollution. Although no silver bullet exists, 78% of the plastic pollution problem can be solved by 2040 through the use of current knowledge and technologies and at a lower net cost for waste management systems compared with that of BAU. However, with long degradation times, even a 78% reduction from BAU pollution rates results in a massive accumulation of plastic waste in the environment. Moreover, even if this system change is achieved, plastic production and unsound waste management activities will continue to emit large quantities of GHGs. Further innovation in resource-efficient and low-emission business models, reuse and refill systems, sustainable substitute materials, waste management technologies, and effective government policies are needed. Such innovation could be financed by redirecting existing and future investments in virgin plastic infrastructure. Substantial commitments to improving the global plastic system are required from businesses, governments, and the international community to solve the ecological, social, and economic problems of plastic pollution and achieve near-zero input of plastics into the environment.

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36. Excluding microplastic pollution, the P_2O model estimates that 9.8 Mt/year [7.7, 12] of plastic pollution enters aquatic systems in 2016 and 16 Mt/year [12, 20] in 2025. These outputs closely align with ranges reported by Jambeck *et al.* (*5*), who report a midpoint of 9.1 Mt/year (25% of mismanaged waste entering the ocean) [5.5 Mt/year for 15%; 14.6 Mt/year for 40%] in 2015 and 17.5 Mt/year [10.5, 28] in 2025. Estimated masses of mismanaged waste reported here (for 2016, 87 Mt [81, 93]; for 2020, 108 Mt [101, 126]) are higher than, but in the same order of magnitude, as those reported by Jambeck *et al.* (*5*) (2016, 36.5 Mt; 2020, 69.9 Mt). This is unsurprising because Jambeck *et al.* (*5*) do not estimate mismanaged waste generated >50 km from the coast. In early model time steps, estimated mismanaged MSW presented here (2016, 87 Mt [81, 93]; 2020, 108 Mt [101, 126]) align well with those presented by Lebreton and Andrady (*2*) (2015, 80 Mt [60, 99]; 2020, 96 Mt [75, 115]). Estimates of mismanaged MSW from the two models diverge into the future; we estimated 228 Mt [213, 252] in 2040, whereas Lebreton and Andrady (*2*) estimated 155 Mt [118, 188]. This divergence may be due to several differences among the models in urban/rural population splits and constraints on waste management and recycling capacities applied in P_2O.
37. Reported results represent model output when inputs are assumed to have no error. 95% CIs were calculated by using Monte Carlo sampling (SM section 5.6). Hereafter, values in square brackets represent the lower and upper bounds of the CI.
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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S6
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Science

Evaluating scenarios toward zero plastic pollution

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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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