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Title: Evaluating Scenarios Toward Zero Plastic Pollution

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Abstract:

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.

One-sentence summary:

Immediate, globally coordinated action on pre- and post-consumption solutions can reduce plastic pollution rates by nearly 80% by 2040

Main Text:

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

approximately 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 – remains unknown.

A growing body of evidence points to a broad range of detrimental effects of plastic pollution. Nearly 700 marine species and over 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 impacts 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 costs of plastic pollution on fishing, tourism and shipping have been estimated at USD 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 though 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 post-consumption 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) while the Basel Convention was amended to regulate the international trade of plastic waste (27). The scientific community and non-governmental 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$_2$O) model. P$_2$O 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 (Fig. S1-S2) and four sources of primary microplastics (i.e., those entering the environment as microplastics; Supplementary

Materials (SM) Section 15; Fig. S3-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).

Projected growth in demand for plastic was calculated 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 (e.g., collection costs, collection and processing rates, recycling recovery value) and rates of primary microplastic generation vary by geography and plastic category/source (6, 32–34). To account for these differences, the global population was split across eight geographic archetypes based on 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 multi-material/multi-layer. 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 2016-2040. Scenarios were defined by four high-level classes of interventions (reduce, substitute, recycle, 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 post-collection 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, 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 using Monte Carlo sampling. Data inputs and assigned uncertainties are described in supplemental material (SM Section 5.6). In the absence of datasets with which to formally validate the model, sensitivity analyses were conducted 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 against 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 2016-2040, the annual rate of macro- and microplastic entering aquatic systems from land increased 2.6-fold (Table 1, Fig. 1C). Over the same period, the rate of plastic pollution retained in terrestrial systems increased 2.8-fold (Table 1, Fig. 1D).

When current commitments to reducing plastic pollution were modeled assuming full implementation (SM Section 9.1), annual plastic pollution rates into aquatic and terrestrial

environments decreased by only 6.6% [95% Confidence Interval: 5.4, 7.9] (37) and 7.7% [5.2, 10] by 2040, respectively (Fig. 1A). 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 t reduction in plastic MSW mass (i.e., through reduce and substitute interventions) decreased aquatic plastic pollution by an average of 0.088 t in low and middle-income archetypes and an average of 0.0050 t 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 t decrease in aquatic plastic pollution, while a similar decrease in post-collection mismanaged waste produced an average 0.10 t decrease in aquatic plastic pollution.

Scenarios to Reduce Plastic Pollution

The focus of plastic pollution reduction strategies can be broadly partitioned into upstream (pre-consumption, e.g., reducing demand) and downstream (post-consumption, e.g., 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 based on historical trends and expert panel consensus assessment (SM Section 1). In a limited number of cases where data were not available in the published literature, we conducted interviews with industry experts or purchased proprietary data from industry market research databases. Compared to BAU, the

annual combined terrestrial and aquatic plastic pollution rates were reduced by 57% in 2040 [45, 69] under the 'Collect and Dispose' scenario, and by 45% [35, 54] under the 'Recycling' scenario (Fig. 1A, B).

Strategies focused on upstream (pre-consumption) 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). Fifteen major plastic applications were assessed against four criteria for technology readiness and unintended consequences related to health/food safety, consumer acceptance (e.g., convenience, climate change impacts) and affordability (Tables S21-S22). The feasibility of substitution with alternative material was assessed 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 while annual plastic production decreased by 47% [44, 49]. Consequently, plastic production in 2040 under the 'Reduce and Substitute' scenario (220 Mt/y [200, 240]) was similar to production in 2016 (210 Mt/y [200, 230]).

Neither pre- nor post-consumption interventions alone are sufficient to address the plastic problem. Combining the maximum foreseen application of pre- and post-consumption 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 (Table 1, Fig. 1A, B). 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 (Table 1, Fig. 1C, D).

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 (Table 1, Fig. 2A). 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 towards 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 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 due to 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 significant 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 (i.e., 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), approximately 1 and 2 times the total annual plastic production in 2016, respectively. If implementation of interventions is delayed 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 multi-material 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 mono-material plastic production (20 Mt/y [19, 21]).

Due to 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 mono-material plastic (33% [28, 37]) (Fig. 5A). In comparison, only 5.0% [4.2, 5.4] of recycled material was derived from multi-material/multilayer waste plastic (Fig. 5A).

The diversity of polymer types, surface contamination and low density of post-consumer 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. 5B, 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. 5B, C). Technologies to capture microplastics, which often rely on stormwater and wastewater management and treatment, are rarely economically feasible – even in wealthy regions – due to 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 post-consumer plastic waste collected for recycling in 2016. To incentivize the collection of low-value plastics (flexible monomaterial and multimaterial / 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).

Mismanaged plastic waste (i.e., 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, approximately 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 via 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.

Though not strictly mismanaged, the net export of waste from high-income to upper- and lower-middle income countries grew from 2.7 Mt/y [2.4, 4.7] in 2016 to 3.8 Mt/y [0.7, 7.2] in 2040 under BAU. Though a comparatively small amount, these exports have the potential to increase the fraction of mismanaged plastic waste, as 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 the ocean 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 which 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 which shed light on the importance of post-collection 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 post-consumption solutions could reverse the increasing trend of environmental plastic pollution. While no silver bullet exists, 78% of the plastic pollution problem can be solved by 2040 using current knowledge and technologies and at a lower net cost for waste management systems compared to 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.

References and Notes:

1.	R. Geyer, J. R. Jambeck, K. L. Law, Production, use, and fate of all plastics ever made. Sci. Adv. **3** (2017).

2.	L. Lebreton, A. Andrady, Future scenarios of global plastic waste generation and disposal. Palgrave Commun. **5** (2019).

3.	C. A. Velis, D. Lerpiniere, M. Tsakona, "Prevent marine plastic litter - now!" (International Solid Waste Association, Vienna, 2017).

4.	D. C. Wilson, C. A. Velis, Waste management – still a global challenge in the 21st century: an evidence-based call for action. Waste Manag. Res. **33**, 1049–1051 (2015).

5.	J. R. Jambeck et al., Plastic waste inputs from land into the ocean. Science. **347**, 768–771 (2015).

6.	J. Boucher, D. Friot, "Primary microplastics in the oceans: a global evaluation of sources" (IUCN, Gland, Switzerland, 2017).

7.	S. C. Gall, R. C. Thompson, The impact of debris on marine life. Mar. Pollut. Bull. **92**, 170–179 (2015).

8.	C. M. Rochman et al., The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. Ecology. **97**, 302–312 (2016).

9.	E. Huerta Lwanga et al., Field evidence for transfer of plastic debris along a terrestrial food chain. Sci. Rep. **7**, 14071 (2017).

10.	K. J. Wyles, S. Pahl, K. Thomas, R. C. Thompson, Factors that can undermine the psychological benefits of coastal environments: exploring the effect of tidal state, presence, and type of litter. Environ. Behav. **48**, 1095–1126 (2016).

11. J. Fobil, J. Hogarh, The dilemmas of plastic wastes in a developing economy: proposals for a sustainable management approach for Ghana. West African J. Appl. Ecol. **10** (2009).

12. E. Boelee, G. Geerling, B. van der Zaan, A. Blauw, A. D. Vethaak, Water and health: from environmental pressures to integrated responses. Acta Trop. **193**, 217–226 (2019).

13. United Nations Environment Programme, "Valuing plastics: the business case for measuring, managing and disclosing plastic use in the consumer goods industry" (2014).

14. D. S. Green, B. Boots, D. J. Blockley, C. Rocha, R. Thompson, Impacts of discarded plastic bags on marine assemblages and ecosystem functioning. Environ. Sci. Technol. **49**, 5380–5389 (2015).

15. A. A. de Souza Machado, W. Kloas, C. Zarfl, S. Hempel, M. C. Rillig, Microplastics as an emerging threat to terrestrial ecosystems. Glob. Chang. Biol. **24**, 1405–1416 (2018).

16. L. G. A. Barboza, A. Dick Vethaak, B. R. B. O. Lavorante, A. K. Lundebye, L. Guilhermino, Marine microplastic debris: an emerging issue for food security, food safety and human health. Mar. Pollut. Bull. **133**, 336–348 (2018).

17. D. Peixoto et al., Microplastic pollution in commercial salt for human consumption: a review. Estuar. Coast. Shelf Sci. **219**, 161–168 (2019).

18. J. Zheng, S. Suh, Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Chang. **9**, 374–378 (2019).

19. D. Xanthos, T. R. Walker, International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. Mar. Pollut. Bull. **118**, 17–26 (2017).

20. J. K. Abbott, U. R. Sumaila, Reducing marine plastic pollution: policy insights from economics. Rev. Environ. Econ. Policy. **13**, 327–336 (2019).

21. M. Cordier, T. Uehara, How much innovation is needed to protect the ocean from plastic contamination? Sci. Total Environ. **670**, 789–799 (2019).

22. I. E. Napper, R. C. Thompson, Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea, soil, and open-air over a 3-year period. Environ. Sci. Technol. **53**, 4775–4783 (2019).

23. Ellen MacArthur Foundation, "The New Plastics Economy: rethinking the future of plastics" (2016).

24. E. J. R. Schnurr, et al., Reducing marine pollution from single-use plastics (SUPs): a review. Mar. Pollut. Bull. **137**, 157–171 (2018).

25. P. Dauvergne, The power of environmental norms: marine plastic pollution and the politics of microbeads. Env. Polit. **27**, 579–597 (2018).

26. European Union, "Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment." (2019).

27. United Nations Environment Programme Secretariat of the Basel Convention, "Decision BC-14/13: further actions to address plastic waste under the Basel Convention" (Châtelaine GE, Switzerland, 2018).

28. F. Oosterhuis, E. Papyrakis, B. Boteler, Economic instruments and marine litter control. Ocean Coast. Manag. **102**, 47–54 (2014).

29. United Nations Department of Economic and Social Affairs Population Division, "World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)" (United Nations, New York: United Nations, 2019).

30. S. Kaza, L. Yao, P. Bhada-Tata, F. Van Woerden, What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050 (The World Bank, Washington, DC, 2018).

31. Material Economics, "The Circular Economy - A powerful force for climate mitigation" (Stockholm, 2018).

32. OECD, Environment at a Glance 2015: OECD Indicators (OECD Publishing, Paris, 2015).

33. WRAP, "Defining what's recyclable and best in class polymer choices for packaging" (v1, Banbury, 2019).

34. E. G. Ashton, W. Kindlein, R. Demori, L. H. A. Cândido, R. Mauler, Recycling polymeric multi-material products through micronization. J. Clean. Prod. **116**, 268–278 (2016).

35. OECD, "Improving markets for recycled plastics" (OECD Publishing, Paris, France, 2018).

36. Excluding microplastic pollution, the P_2O model estimates that 9.8 Mt/y [7.7, 12] of plastic pollution enters aquatic systems in 2016 and 16 My/y [12, 20] in 2025. These outputs closely align with ranges reported by Jambeck et al. (5), who report a midpoint of 9.1 Mt/y (25% of mismanaged waste entering the ocean) [5.5 Mt/y for 15%; 14.6 Mt/y for 40%] in 2015 and 17.5 Mt/y [10.5 Mt/y, 28 Mt/y] 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, as 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 while 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% Confidence Intervals (CI) were calculated using Monte Carlo sampling (see SM Section 5.6). Hereafter, values in square brackets represent the lower and upper bounds of the CI.

38. M. Crippa et al., "A circular economy for plastics – insights from research and innovation to inform policy and funding decisions" (European Commission, Brussels, Belgium, 2019).

39. S. Slater, T. Crichton, "Recycling of laminated packaging" (Banbury, UK, 2011).

40. C. A. Velis et al., An analytical framework and tool ('InteRa') for integrating the informal recycling sector in waste and resource management systems in developing countries. Waste Manag. Res. **30**, 43–66 (2012).

41. D. C. Wilson et al., "Wasteaware" benchmark indicators for integrated sustainable waste management in cities. Waste Manag. **35**, 329–342 (2015).

42. K. L. Law, Plastics in the marine environment. Ann. Rev. Mar. Sci. **9**, 205–229 (2017).

43. C. Wiedinmyer, R. J. Yokelson, B. K. Gullett, Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. Environ. Sci. Technol. **48**, 9523–9530 (2014).

44. N. Reyna-Bensusan, D. C. Wilson, P. M. Davy, G. W. Fuller, G. D. Fowler, S. R. Smith, Experimental measurements of black carbon emission factors to estimate the global impact of uncontrolled burning of waste. Atmos. Environ. **213**, 629–639 (2019).

45. C. A. Velis, Circular economy and global secondary material supply chains. Waste Manag. Res. **33**, 389–391 (2015).

46. R. Tramoy et al., Assessment of the plastic inputs from the Seine Basin to the sea using statistical and field approaches. Front. Mar. Sci. **6** (2019).

47. T. van Emmerik, M. Loozen, K. van Oeveren, F. Buschman, G. Prinsen, Riverine plastic emission from Jakarta into the ocean. Environ. Res. Lett. **14**, 084033 (2019).

48. G. F. Schirinzi et al., Riverine anthropogenic litter load to the Mediterranean Sea near the metropolitan area of Barcelona, Spain. Sci. Total Environ. **714**, 136807 (2020).

49. D. C. Wilson, L. Rodic, A. Scheinberg, C. A. Velis, G. Alabaster, Comparative analysis of solid waste management in 20 cities. Waste Manag. Res. **30**, 237–254 (2012).

50. UNEP, "Global waste management outlook" (United Nations Environment Programme, 2015), https://www.unenvironment.org/resources/report/global-waste-management-outlook).

51. University of Leeds, Wasteaware cities indicators: toolkit - Leeds, UK. (2019), (http://benchmark.wasteaware.org/).

52. D. C. Wilson, C. A. Velis, L. Rodic, Integrated sustainable waste management in developing countries. Proc. Inst. Civ. Eng. - Waste Resour. Manag. **166**, 52–68 (2013).

53. D. Hoornweg, P. Bhada-Tata, "What a waste: a global review of solid waste management" (Urban Development & Local Government Unit, The World Bank, Washington, DC, USA, 2012).

54. The World Bank, World Bank country and lending groups (2019).

55. United Nations, "World urbanization prospects: the 2018 revision, online edition" (2018), (https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf).

56. Center for International Earth Science Information Network - CIESIN - Columbia University, "Gridded population of the world, version 4 (GPWv4): population count adjusted to Match 2015 revision of UN WPP country totals, revision 11" (NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY, 2018).

57. B. Lehner, K. Verdin, A. Jarvis, New global hydrography derived from spaceborne elevation data. Eos Trans. AGU. **89**, 93– 94 (2008).

58. H. Pilz, The Potential for Plastic Packaging to Contribute to a Circular and Resource-efficient Economy (Denkstatt, Rome, 2015; https://denkstatt.eu/download/1986/).

59. O. Horodytska, F. J. Valdés, A. Fullana, Plastic flexible films waste management – a state of art review. Waste Manag. **77**, 413–425 (2018).

60. F. Aeschelmann, M. Carus, "Bio-based building blocks and polymers, global capacities and trends 2016-2021" (nova-Institut GmbH, Hürth, 2017), (http://bio-based.eu/downloads/bio-based-building-blocks-and-polymers-global-capacities-and-trends-2016-2021-2/).

61. S. Hann, C. Sherrington, O. Jamieson, M. Hickman, A. Bapasola, "Investigating options for reducing releases in the aquatic environment of microplastics emitted by (but not intentionally added in) products" (Eunomia, 2018).

62. S. Kaza, Yao, L., Bhada-Tata, P., and Van Woerden, F., Country-Level Dataset. What a Waste 2.0 (2018).

63.   G. Hanke, "Marine beach litter in Europe – top items," European Commisson JRC

       Technical Reports (Ispra, 2016).

64.   T. Maes et al., Below the surface: Twenty-five years of seafloor litter monitoring in

       coastal seas of North West Europe (1992–2017). Sci. Total Environ. **630**, 790–798 (2018).

65.   L. Lebreton et al., Evidence that the Great Pacific Garbage Patch is rapidly accumulating

       plastic. Sci. Rep. **8**, 1–15 (2018).

66.   S. Chiba et al., Human footprint in the abyss: 30 year records of deep-sea plastic debris.

       Mar. Policy. **96**, 204–212 (2018).

67.   Ocean Conservancy, "The beach and beyond" (Washington, DC, 2019),

       (https://oceanconservancy.org/blog/2019/09/04/beach-beyond-breaking-2018-

       international-coastal-cleanup-results/).

68.   OECD, Municipal Waste Data (2018), (https://data.oecd.org/waste/municipal-waste.htm).

69.   W. R. Stahel, The circular economy. Nature. **531**, 435–438 (2016).

70.   The World Bank, What a Waste Global Database (2018),

       https://datacatalog.worldbank.org/dataset/what-waste-global-database).

71.   Material Economics, "The circular economy - powerful force for climate mitigation"

       (Stockholm, 2018), (https://materialeconomics.com/publications/the-circular-economy-a-

       powerful-force-for-climate-mitigation-1).

72.   DEFRA, "Defra EV0801 National compositional estimates for local authority collected

       waste and recycling in England, 2010/11." (2013),

       (http://randd.defra.gov.uk/Document.aspx?Document=11714_EV0801summary09-12-

       13.pdf).

73. WRAP, "Rigid plastic packaging in the commercial and industrial sectors" (2016), (http://www.wrap.org.uk/sites/files/wrap/Rigid_Plastic_Packaging_report_0.pdf).

74. H. Thomson, P. Sainsbury, "Plastic spatial flow 2013. An assessment of the quantity of un-recycled plastic in the UK" (2016), (https://www.wrap.org.uk/content/plastics-spatial-flow).

75. WRAP, "PlasticFlow 2025 – plastic packaging flow data report" (Banbury, 2018), (http://www.wrap.org.uk/content/plasticflow-2025-plastic-packaging-flow-data-report.).

76. Eurostat, Packaging waste by waste management operations and waste flow (2019), (https://ec.europa.eu/eurostat/en/web/products-datasets/-/ENV_WASPAC).

77. US Environmental Protection Agency, "Municipal solid waste generation, recycling, and disposal in the United States. tables" (Washington, DC, 2014), (https://www.epa.gov/sites/production/files/2015-12/documents/methodolgy_document_for_selected_municipal_solid_waste_products.pdf).

78. GAIA, "Plastics exposed: how waste assessments and brand audits are helping Philippine cities fight plastic pollution" (Quezon City, Philippines, 2019), (http://www.no-burn.org/wp-content/uploads/PlasticsExposed-2.pdf).

79. "Abidjan, Cote d'Ivoire waste characterization data," Proprietary Data (source shared upon request) (2018).

80. Kashtakari Panchayat, Waste Ventures, "Waste survey data of households across a cross-section of income levels in Pune, India," Proprietary data (source shareable upon request) (2015).

81. "Waste composition data collected from 300 households and 10 businesses in Cat Ba and Ha Long, Vietnam," Proprietary Data (source information available upon request) (2018).

82. Sustainable Waste Indonesia, "Project STOP in Muncar, East Java, Indonesia data per Indonesian standard for municipal solid waste generation (SNI No 19-3964-1995)," Proprietary data (source shareable upon request) (2018).

83. GAIA, "Plastics exposed: how waste assessments and brand audits are helping Philippine cities fight plastic pollution" (Quezon City, Philippines, 2019).

84. B. Milanez, L. M. Massukado, "Caderno de diagnóstico. resíduos sólidos urbanos" (Ipea, Brasilia, 2011).

85. Grand View Research, "Plastic packaging market," Purchased Proproprietary data - for purchase information https://www.grandviewresearch.com/ (2019).

86. Ellen MacArthur Foundation, "Global commitment 2019 progress report" (2019), (https://www.newplasticseconomy.org/about/publications/global-commitment-2019-progress-report).

87. UNEP, "Single-use plastics: a roadmap for sustainability" (Nairobi, 2018).

88. E. Moss, R. Grousset, "The dirty truth about disposable foodware" (2020).

89. UNEP (2020): the UNEP environmental data explorer. United Nations Environ. Program. (2020).

90. RIAA, U.S. recorded music sales volumes by format 1973 to 2018, (https://www.riaa.com/u-s-sales-database/).

91. Goldman Sachs, "China: clean energy: LED," Global Investment Research (2012), (http://pg.jrj.com.cn/acc/Res/CN_RES/INDUS/2012/12/18/51c0f637-b20a-4a92-bd53-3afeddc4375c.pdf).

92. GDP growth (annual %). World Bank Natl. accounts data, OECD Natl. Accounts data files (2019), (https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG).

93. R. Linzner, U. Lange, Role and size of informal sector in waste management – a review. Proc. Inst. Civ. Eng. - Waste Resour. Manag. **166**, 69–83 (2013).

94. D. C. Wilson, C. Velis, C. Cheeseman, Role of informal sector recycling in waste management in developing countries. Habitat Int. **30**, 797–808 (2006).

95. M. Asim, S. A. Batool, M. N. Chaudhry, Scavengers and their role in the recycling of waste in Southwestern Lahore. Resour. Conserv. Recycl. **58**, 152–162 (2012).

96. F. Chen, Z. Luo, Y. Yang, G. J. Liu, J. Ma, Enhancing municipal solid waste recycling through reorganizing waste pickers: A case study in Nanjing, China. Waste Manag. Res. 36, 767–778 (2018).

97. K. Khan, F. Alam, H. Chowdhury, "Impact of climate change on power plants in Bangladesh," in Proceedings of the International Conference on Mechanical Engineering 2011, P. M. Ali, Ed. (Dhaka, 2011), vol. 1, pp. 1–6.

98. Y. Hayami, A. K. Dikshit, S. N. Mishra, Waste pickers and collectors in Delhi: Poverty and environment in an urban informal sector. J. Dev. Stud. **42**, 41–69 (2006).

99. A. Majeed, S. A. Batool, M. N. Chaudhry, Informal waste management in the developing world: economic contribution through integration with the formal sector. Waste and Biomass Valorization. **8**, 679–694 (2017).

100. B. Steuer, R. Ramusch, S. Salhofer, Is there a future for the informal recycling sector in urban China? Detritus (2018), doi:10.31025/2611-4135/2018.13725.

101. RDC-Environment & Pira International, "Evaluation of costs and benefits for the achievement of reuse and recycling targets for the different packaging materials in the frame of the packaging and packaging waste directive 94/62/EC – Final consolidated report" (2003), (https://ec.europa.eu/environment/waste/studies/packaging/costsbenefits.pdf).

102. Chintan Environmental Research and Action Group, "InFORMAL-formal. Creating opportunities for the informal waste recycling sector in Asia" (Delhi, India, 2005).

103. V. Ibáñez-Forés, C. Coutinho-Nóbrega, M. D. Bovea, C. de Mello-Silva, J. Lessa-Feitosa-Virgolino, Influence of implementing selective collection on municipal waste management systems in developing countries: A Brazilian case study. Resour. Conserv. Recycl. **134**, 100–111 (2018).

104. S. E. Vergara, A. Damgaard, D. Gomez, The efficiency of informality: quantifying greenhouse gas reductions from informal recycling in Bogotá, Colombia. J. Ind. Ecol. **20**, 107–119 (2016).

105. A. Chandramohan, C. Ravichandran, V. Sivasankar, Solid waste, its health impairments and role of rag pickers in Tiruchirappalli city, Tamil Nadu, Southern India. Waste Manag. Res. **28**, 951–958 (2010).

106. A. R. Putri, T. Fujimori, M. Takaoka, Plastic waste management in Jakarta, Indonesia: evaluation of material flow and recycling scheme. J. Mater. Cycles Waste Manag. **20**, 2140–2149 (2018).

107. S. Sasaki, T. Araki, Estimating the possible range of recycling rates achieved by dump waste pickers: the case of Bantar Gebang in Indonesia. Waste Manag. Res. **32**, 474–481 (2014).

108. S. Sasaki, T. Araki, A. H. Tambunan, H. Prasadja, Household income, living and working conditions of dumpsite waste pickers in Bantar Gebang: toward integrated waste management in Indonesia. Resour. Conserv. Recycl. **89**, 11–21 (2014).

109. S. Sasaki, K. Watanabe, N. Widyaningsih, T. Araki, Collecting and dealing of recyclables in a final disposal site and surrounding slum residence: the case of Bantar Gebang, Indonesia. J. Mater. Cycles Waste Manag. **21**, 375–393 (2019).

110. PlasticsEurope, "Plastics - the facts 2018: an analysis of European plastics production, demand and waste data" (2018), (https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018 _AF_web.pdf).

111. U.S. Environmental Protection Agency, "MSW characterization methodology" (2007), (https://www.epa.gov/sites/production/files/2015-09/documents/06numbers.pdf).

112. European Commission, 2005/270/EC: Commission Decision of 22 March 2005 establishing the formats relating to the database system pursuant to Directive 94/62/EC of the European Parliament and of the Council on packaging and packaging waste (notified under document number C(2005. Doc. 32005D0270 (2005), , doi:http://data.europa.eu/eli/dec/2005/270/oj.

113. Plastic Waste Management Institute Japan, Plastic products, plastic waste and resource recovery [2017]. PWMI Newsl. **48** (2019) (https://www.pwmi.or.jp/ei/siryo/ei/ei_pdf/ei48.pdf).

114. M. Hestin, T. Faninger, L. Milios, "Increased EU plastics recycling targets: environmental, economic and social impact assessment final report" (2015).

115. European Commission, "Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives" (European Commission, Brussels, 2008).

116. European Commission, "European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste" (1994), (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31994L0062:EN:HTML).

117. 4R Sustainability Inc., "Conversion technology: A complement to plastic recycling" (2011), (https://plastics.americanchemistry.com/Plastics-to-Oil/).

118. Closed Loop Partners, "Accelerating circular supply chains for plastics: a landscape of transformational technologies that stop plastic waste, keep materials in play and grow markets" (2019), (https://www.closedlooppartners.com/wp-content/uploads/2019/04/CLP_Circular_Supply_Chains_for_Plastics.pdf).

119. Deloitte, "Increased EU plastics recycling targets: environmental, economic and social impact assessment" (London, 2015), (https://743c8380-22c6-4457-9895-11872f2a708a.filesusr.com/ugd/0af79c_d3c616e926e24896a8b82b833332242e.pdf).

120. WRAP, "PlasticFlow 2025 estimates the quantity of plastic packaging placed on the market and recycled from 2017 to 2025 and the probability of compliance with national and European recycling targets" (2018), (https://www.wrap.org.uk/content/plasticflow-2025-plastic-packaging-flow-data-report).

121. Ricardo Energy & Environment, "Plastic to fuel market review" (2017), (https://ee.ricardo.com/ (purchased report)).

122.   United Nations, UN Comtrade Database (2019), (https://comtrade.un.org/).

123.   C. Staub, Malaysia outlines new plastic import criteria. Plast. Recycl. Updat. A Resour. Recycl. Inc. Publ. (2018), (https://resource-recycling.com/plastics/2018/10/31/malaysia-outlines-new-plastic-import-criteria/).

124.   R. S. Bedi, Few factories complying with plastic waste regulations. Star Online. **2019** (2019), (https://www.thestar.com.my/news/nation/2019/01/16/few-factories-complying-with-plastic-waste-regulations).

125.   C. Staub, July trade analysis: Plastics imports nosedive in Thailand. Plast. Recycl. Updat. A Resour. Recycl. Inc. Publ. (2018), (https://resource-recycling.com/recycling/2018/09/11/july-trade-analysis-plastics-imports-nosedive-in-thailand/).

126.   C. Staub, Exports to Thailand collapse after ban. Plast. Recycl. Updat. A Resour. Recycl. Inc. Publ. (2018), (https://resource-recycling.com/plastics/2018/09/06/exports-to-thailand-collapse-after-ban/).

127.   C. Staub, Scrap plastic exports plummet 43% this year. Plast. Recycl. Updat. A Resour. Recycl. Inc. Publ. (2019), (https://resource-recycling.com/recycling/2019/08/06/scrap-plastic-exports-plummet-43-this-year-paper-stable/).

128.   A. L. Brooks, S. Wang, J. R. Jambeck, The Chinese import ban and its impact on global plastic waste trade. Sci. Adv. **4**, eaat0131 (2018).

129.   UN Trade Statistics, Harmonized commodity description and coding systems (HS) (2017), (https://unstats.un.org/unsd/tradekb/Knowledgebase/50018/Harmonized-Commodity-Description-and-Coding-Systems-HS).

130. A. Bagchi, Design for landfills and integrated solid waste management (Wiley, Hoboken, NJ, 3rd Editio., 2004).

131. UN Environment, "Mapping of global plastics value chain and plastics losses to the environment: With a particular focus on marine environment" (Ryberg, Morten W. Laurent, Alexis Hauschild, Michael, United Nations Environment Programme, Nairobi, Kenya, 2018).

132. J. Boucher et al., (Micro) plastic fluxes and stocks in Lake Geneva basin. TrAC Trends Anal. Chem. **112**, 66–74 (2019).

133. Ocean Conservancy, "Stemming the tide: land-based strategies for a plastic - free ocean" (2015), (https://oceanconservancy.org/wp-content/uploads/2017/04/full-report-stemming-the.pdf).

134. L. C. M. Lebreton et al., River plastic emissions to the world's oceans. Nat. Commun. **8**, 15611 (2017).

135. C. Schmidt, T. Krauth, S. Wagner, Export of plastic debris by rivers into the sea. Environ. Sci. Technol. **51**, 12246–12253 (2017).

136. Sub Direktorat Statistik Lingkungan Hidup, J.-I. Central Bureau of Statistics, S. D. of E. Statistics, "Indikator perilaku peduli lingkungan hidup (2014 environmental care behavior indicators)" (Jakarta, 2015).

137. Coastal Cleanup Reports, The International Coastal Cleanup (https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/annual-data-release/).

138. GESAMP, "Sources, fate and effects of microplastics in the marine environment: part two of a global assessment" (International Maritime Organization, London, UK, 2016).

139. A. Winkler et al., Does mechanical stress cause microplastic release from plastic water bottles? Water Res. **166** (2019), doi:10.1016/j.watres.2019.115082.

140. Eunomia, "Plastics in the marine environment" (Bristol, UK, 2016).

141. D. Kawecki, B. Nowack, Polymer-specific modeling of the environmental emissions of seven commodity plastics as macro- and microplastics. Environ. Sci. Technol. **53**, 9664–9676 (2019).

142. R. N. Thompson, C. A. Nau, C. H. Lawrence, Identification of vehicle tire rubber in roadway dust. Am. Ind. Hyg. Assoc. J. **27**, 488–495 (1966).

143. P. Sundt, P.-E. Schulze, F. Syversen, "Sources of microplastic- pollution to the marine environment. Report to the Norwegian Environment Agency" (2014), (https://www.miljodirektoratet.no/globalassets/publikasjoner/M321/M321.pdf).

144. C. Lassen et al., "Microplastics: Occurrence, effects and sources of releases to the environment in Denmark" (Copenhagen, 2015), (https://orbit.dtu.dk/files/118180844/Lassen_et_al._2015.pdf).

145. A. R. Essel R, Engel L, Carus M, "Sources of microplastics relevant to marine protection in Germany" (Umwelt Bundesamt, Dessau-Roßlau, 2015).

146. K. Magnusson et al., Swedish sources and pathways for microplastics to the marine environment. A review of existing data. IVL Sven. miljöinstitutet, 1–89 (2016).

147. J. M. Panko, J. Chu, M. L. Kreider, K. M. Unice, Measurement of airborne concentrations of tire and road wear particles in urban and rural areas of France, Japan, and the United States. Atmos. Environ. **72**, 192–199 (2013).

148. H. ten Broeke, J. Hulskotte, H. D. van der Gon, "Road Traffic Tyre Wear," Emission estimates for diffuse sources Netherlands Emission Inventory (2008),

(http://www.emissieregistratie.nl/erpubliek/documenten/Water/Factsheets/English/Road traffic tyre wear.pdf).

149. W. R. Pierson, W. W. Brachaczek, Airborne particulate debris from rubber tires. Rubber Chem. Technol. **47**, 1275–1299 (1974).

150. S. Wagner et al., Tire wear particles in the aquatic environment - A review on generation, analysis, occurrence, fate and effects. Water Res. **139**, 83–100 (2018).

151. Federal Highway Administration Department of Transportation, "Traffic volume trends US. February 2013" (2013), (https://www.fhwa.dot.gov/policyinformation/travel_monitoring/13febtvt/13febtvt.pdf).

152. The World Bank, "International tourism, number of departures. World Tourism Organization, Yearbook of Tourism Statistics, Compendium of Tourism Statistics and data files" (2018), (https://data.worldbank.org/indicator/ST.INT.DPRT).

153. P. Jan Kole, A. J. Löhr, F. G. A. J. Van Belleghem, A. M. J. Ragas, Wear and tear of tyres: A stealthy source of microplastics in the environment. Int. J. Environ. Res. Public Health. **14** (2017), doi:10.3390/ijerph14101265.

154. K. M. Unice et al. Characterizing export of land-based microplastics to the estuary - Part I: Application of integrated geospatial microplastic transport models to assess tire and road wear particles in the Seine watershed. Sci. Total Environ. **646**, 1639–1649 (2019).

155. W. P. Albertone G., Allen S., Redpath A. ed. Strandell H., "Globalization patterns in EU trade and investments 2017 edition" (Eurostat, European Union, Luxembourg, 2017), , doi:10.2785/65836.

156. R. Dris, J. Gasperi, M. Saad, C. Mirande, B. Tassin, Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? Mar. Pollut. Bull. **104**, 290–293 (2016).

157. J. Sun, X. Dai, Q. Wang, M. C. M. van Loosdrecht, B. J. Ni, Microplastics in wastewater treatment plants: Detection, occurrence and removal. Water Res. **152** (2019), pp. 21–37.

158. Textile Exchange, "Prefered fiber & materials, Market report 2018" (2018).

159. WTO, in World Trade Statistical Review 2017, A. Martin, S. Marin-Pache, Eds. (World Trade Organization, Washington, DC, 2017; https://www.wto.org/english/res_e/statis_e/wts2017_e/WTO_Chapter_09_tables_e.pdf), pp. 96–177.

160. Population connected to wastewater treatment. United Nations Stat. Div. (2018), (http://data.un.org/Data.aspx?d=ENV&f=variableID:164).

161. Eurostat, Wastewater treatment plants by treatment level [env_ww_plt] (2019), (https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_ww_plt&lang=en).

162. WWAP (United Nations World Water Assessment Programme), "The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource" (UNESCO, Paris, 2017), (https://unesdoc.unesco.org/ark:/48223/pf0000247153).

163. Q. H. Zhang et al., Current status of urban wastewater treatment plants in China. Environ. Int. **92**–**93**, 11–22 (2016).

164. F. Zurita, E. D. Roy, J. R. White, Municipal wastewater treatment in Mexico: Current status and opportunities for employing ecological treatment systems. Environ. Technol. (United Kingdom). **33**, 1151–1158 (2012).

165. M. Seneviratne, "Wastewater treatment technologies," ZDHC Roadmap to Zero Program (ZDHC Foundation, Amsterdam, 2018), (https://uploads-ssl.webflow.com/5c4065f2d6b53e08a1b03de7/5db6f50d7a90f4e4a47725cf_Wastewater_Treatment_Technologies_for_the_Textile_Industry-FINAL.pdf).

166. M. Bergmann et al., White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. **5**, eaax1157 (2019).

167. M. Yurtsever, Tiny, shiny, and colorful microplastics: Are regular glitters a significant source of microplastics? Mar. Pollut. Bull. **146**, 678–682 (2019).

168. Amec Foster Wheeler Environment & Infrastructure UK Ltd., "Intentionally added microplastics in products" (London, UK, 2017), (https://ec.europa.eu/environment/chemicals/reach/pdf/39168 Intentionally added microplastics - Final report 20171020.pdf).

169. HM Treasury, The Green Book: Central Government Guidance on Appraisal and Evaluation (OGL, London, UK, ed. 2018, 2018; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf).

170. G. Heal, Valuing the future: economic theory and sustainability (Economics for a Sustainable Earth Series, Columbia University Press, New York, 2000).

171. U.R. Sumaila, Intergenerational cost–benefit analysis and marine ecosystem restoration. Fish Fish (Oxf). **5**, 329–343 (2004).

172. F. Wagner, Renewables in Future Power Systems: Implications of Technological Learning and Uncertainty (Springer International Publishing, Cham, ed. 1, 2014), (http://link.springer.com/10.1007/978-3-319-05780-4).

173. J. D. Farmer, F. Lafond, How predictable is technological progress? Res. Policy. **45**, 647–665 (2016).

174. D. Hogg, "Costs for municipal waste management in the EU" (Bristol, UK, 2002), (https://ec.europa.eu/environment/waste/studies/pdf/eucostwaste.pdf).

175. Material Economics, "Sustainable packaging – the role of materials substitution" (Stockholm, 2018), (https://materialeconomics.com/material-economics-sustainable-packaging.pdf?cms_fileid=cb5800d42dbe94804e0bd9cded60b453 or https://materialeconomics.com/publications/sustainable-packaging).

176. B. Choi, S. Yoo, S. Il Park, Carbon footprint of packaging films made from LDPE, PLA, and PLA/PBAT blends in South Korea. Sustain. **10**, 2369 (2018).

177. WRAP Cymru, Eunomia Research and Consulting, WRAP Cymru, "Kerbside collections options: Wales" (Cardiff, 2011).

178. A. J. Dubanowitz, thesis, Columbia University. (2000).

179. Eurostat, "Municipal waste by waste operations" (2018), (https://ec.europa.eu/eurostat/web/waste/municipal-waste-generation-and-treatment-by-treatment-method).

180. T. Elliott, L. Elliott, "A plastic future: plastic consumption and waste management in the UK" (Bristol, 2018).

181. DEFRA, "Consultation stage impact assessment on the proposal to ban the distribution and/or sale of plastic drinking straws in England" (2018).

182. ICF, Eunomia, "Assessment of measures to reduce marine litter from single use plastics" (2018), (http://ec.europa.eu/environment/waste/pdf/Study_sups.pdf).

183. C. E. Scholefield S., French W., "Collection of food and drink cartons at the kerbside: guidance for local authorities and waste contractors" (2017), (http://www.wrap.org.uk/sites/files/wrap/WRAP_2923_Collection-food-drink-cartons-kerbside-guidance.pdf).

184. H. Clancy, "P&G's circular economy strategy now includes water and (yes) diapers." GreenBiz (2020) (https://www.greenbiz.com/article/pgs-circular-economy-strategy-now-includes-water-and-yes-diapers).

185. WRAP UK, "Collection and Sorting of Household Rigid Plastic Packaging" (2019), (http://www.wrap.org.uk/content/collection-and-sorting-household-rigid-plastic-packaging).

186. A. Nonclercq, thesis, Delft University of Technology (2016).

187. Green Blue Institute, "Closing the loop - design for recovery guidelines: paper packaging" (Charlottesville, VA, 2011), (http://fpwg.info/wp-content/uploads/2015/08/ctl-design-for-recovery-paper.pdf).

188. Confederation of Paper Industries, "Design for the future: paper and board packaging recyclability guidelines" (Wiltshire, UK, 2019), (https://paper.org.uk/PDF/Public/Publications/Guidance Documents/CPI Recyclability Guidelines Final.pdf).

189. Food and Agriculture Organization of the United Nations, "Global forests products, facts and figures" (2016), (www.fao.org/forestry/statistics).

190. US Environmental Protection Agency, "Materials Municipal Waste Stream 1960 - 2015" (Washington, DC, 2015),

(https://edg.epa.gov/data/PUBLIC/OLEM/Materials_Municipal_Waste_Stream_1960_to_2015.xlsx).

191. M. Fernandez., Waste-to-energy in China: perspectives. BioEnergy Consult (2018).

192. H. Hu, X. Li, A. Nguyen, P. Kavan, A critical evaluation of waste incineration plants in Wuhan (China) based on site selection, environmental influence, public health and public participation. Int. J. Environ. Res. Public Health. **12**, 7593–7614 (2015).

193. Y. Hu, H. Cheng, S. Tao, The growing importance of waste-to-energy (WTE) incineration in China's anthropogenic mercury emissions: Emission inventories and reduction strategies. Renew. Sustain. Energy Rev. Elsevier. **97(C)**, 119–137 (2018).

194. China YearBooks, China Statistical Yearbook 2018 (China Statistics Press, 2018; https://www.chinayearbooks.com/china-statistical-yearbook-2018.html).

195. L. Ji et al., Municipal solid waste incineration in China and the issue of acidification: A review. Waste Manag. Res. **34**, 280–297 (2016).

196. C.R.K.J. Paulraj, M.A. Bernard, J. Raju, M. Abdulmajid, Sustainable waste management through waste to energy technologies in India – opportunities and environmental impacts. Int. J. Renew. Energy Res. **9** (2019).

197. Y. Wang, A. Boggio-Marzet, Evaluation of eco-driving training for fuel efficiency and emissions reduction according to road type. Sustain. **10** (2018), doi:10.3390/su10113891.

198. D. Silvestro, G. Gilelen, in European TRWP Platform - 2nd Technical Meeting. (2019).

199. Interview with Andrej Krzan, PlanetCare, based on in-house measurement of their filters [28/01/2019].

200. Water and sanitation - United Nations sustainable develompent. Sustain. Dev. Goals, UN (2019), (https://www.un.org/sustainabledevelopment/water-and-sanitation/).

201. C. Edwards, J. M. Fry, "Life cycle assessment of supermarket carrier bags: a review of the bags available in 2006" (Environment Agency, Bristol, UK, 2011), (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291023/scho0711buan-e-e.pdf).

202. DEFRA, "Single-use plastic carrier bags charge: data in England for 2016 to 2017" (London, UK, 2018), (https://data.gov.uk/dataset/682843a8-168c-4056-b6fe-741161a39f60/single-use-plastic-carrier-bags-charge-data-for-england).

203. DEFRA, "Single-use plastic carrier bags charge: data in England for 2017 to 2018" (London, UK, 2018), (https://www.gov.uk/government/publications/carrier-bag-charge-summary-of-data-in-england/single-use-plastic-carrier-bags-charge-data-in-england-for-2017-to-2018).

204. S. Aumónier, M. Collins, P. Garrett, "An updated lifecycle assessment study for disposable and reusable nappies" (Environment Agency, Bristol, UK, 2008), (http://randd.defra.gov.uk/Document.aspx?Document=WR0705_7589_FRP.pdf).

205. M. Cioci, "The cost and environmental benefits of using reusable food ware in schools: a Minnesota case study" (Saint Paul, MN, 2014), (www.pca.state.mn.us/sites/default/files/p-p2s6-16.pdf).

206. Rethink Disposable, "Institutional case study: Genentech's Café B33" (2017), (http://www.rethinkdisposable.org/file/329/download?token=GPokz_d1).

207. Ellen MacArthur Foundation, "Reuse - Rethinking Packaging" (2017), (https://www.ellenmacarthurfoundation.org/assets/downloads/Reuse.pdf).

208. Svenska Retursystem, Reusable crates (2019), (http://www.retursystem.se/en/how-it-works/reusable-crates/).

209. C. Tua, L. Biganzoli, M. Grosso, L. Rigamonti, Life cycle assessment of reusable plastic crates (RPCs). Resources. **8**, 110 (2019).

210. US Environmental Protection Agency, "Advancing sustainable materials management: 2015 fact sheet" (Washington, DC, 2015), (https://www.epa.gov/sites/production/files/2018-07/documents/2015_smm_msw_factsheet_07242018_fnl_508_002.pdf).

211. Atulesh, Recycling paper from paper waste (2017), (https://www.wealthywaste.com/recycling-paper-from-paper-waste).

212. Philippine Paper Manufacturer's Association Inc., "The use of paper and measures to improve its recycling rate in the Philippines" (Mandaluyong City, 2017).

213. Consumer Goods Forum, "Blueprint for packaging waste management: an FMCG view" (Issy-les-Moulineaux, France, 2019).

214. OECD, OECD Exchange rates (indicator). OECD (2019), , doi:10.1787/037ed317-en.

215. PlasticsEurope, "Plastics – the Facts 2016. An analysis of European plastics production, demand and waste data" (Brussels, 2017), (https://www.plasticseurope.org/application/files/4315/1310/4805/plastic-the-fact-2016.pdf).

216. Government of Kerala, "Modified guidelines on specifications, standards, unit costs, O&M protocol, subsidy norms and contract conditions for solid waste treatment plants to be set up or promoted by local governments using vermi compositing, windrow composting and bio-methanation technologies" (Thiruvananthapuram, Kerala, 2011), (http://sanitation.kerala.gov.in/wp-content/uploads/2019/04/g.o-73_2011.pdf).

217. US Environmental Protection Agency, "Volume-to-weight conversion factors" (Washington, DC, 2016), (https://www.epa.gov/sites/production/files/2016-04/documents/volume_to_weight_conversion_factors_memorandum_04192016_508fnl.pdf).

218. M. Patel, N. Von Thienen, E. Jochem, E. Worrell, Recycling of plastics in Germany. Resour. Conserv. Recycl. **29**, 65–90 (2000).

219. Plastics Information Europe, PET Recyclate Prices (2019), (https://pieweb.plasteurope.com/default.aspx?pageid=21002 (purchased proprietary data)).

Supplementary Materials:

Materials and Methods

Figures S1-S6

Tables S1-S75

References (49-219)

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 (Mt/y +/- 95% CI) by scenario, 2016 – 2040. Scenarios: '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 global commitments to reduce plastic use and increase recycling announced before June 2019 are implemented prior to 2040. A time series for this scenario is not presented because timelines for implementation are unknown. (B) Kernel density estimates for plastic pollution (Mt) in 2040 by scenario. Boxplots of plastic pollution entering (C) aquatic and (D) terrestrial ecosystems by scenario for beginning, middle, and end years of scenario implementation.

Fig. 2 Fate for all municipal solid waste plastic, 2016-2040, under the 'System Change' scenario (SCS). (A) Annual mass of plastic (Mt/y) for each of five end-of-life fates. (B) Mass of plastic utility (Mt/y) addressed per modeled intervention in 2040, following 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.

Fig. 3. Present value costs for the management (i.e., collection, sorting, recycling, and disposal) of plastic municipal solid waste by scenario, 2016 -2040. Costs (Billion 2018 USD

+/- 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: Business as Usual' (BAU), 'Collect and Dispose" scenario (CDS), 'Recycling' scenario (RES), 'Reduce and Substitute' scenario (RSS), and 'System Change' scenario (SCS).

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

Fig. 5. Fate of plastic municipal solid waste (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. The proportion of plastic pollution (+/- 95% CI) entering (B) global aquatic and (C) terrestrial systems by plastic type, 2016 – 2040.
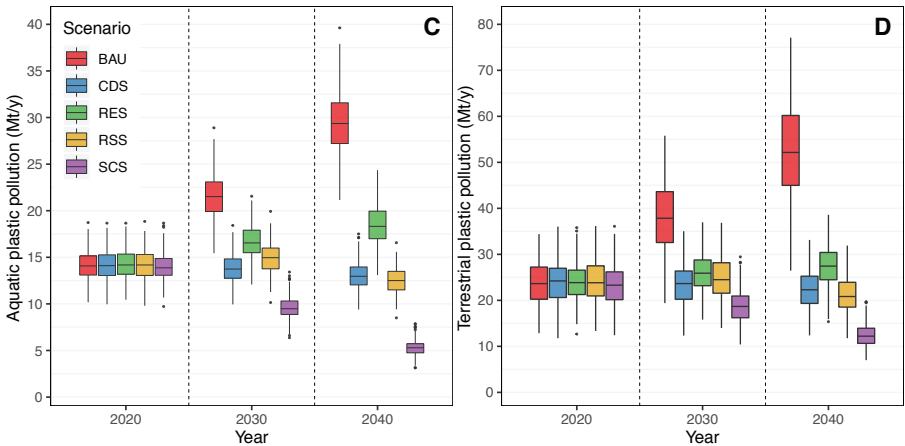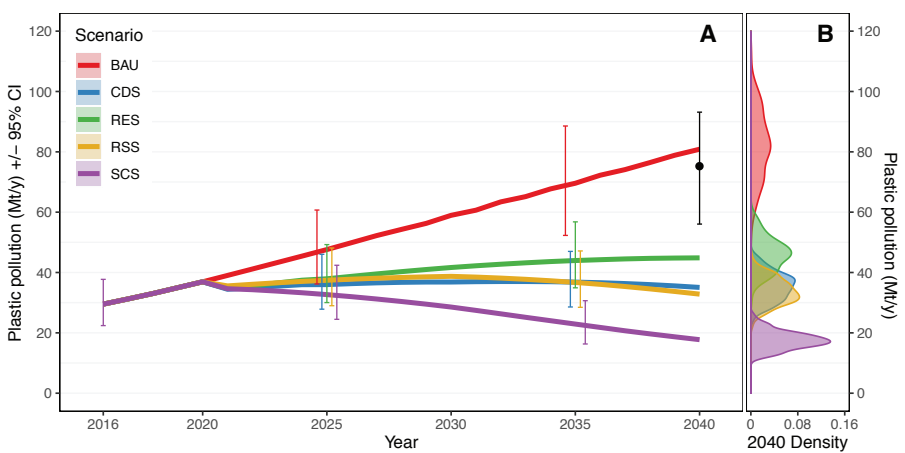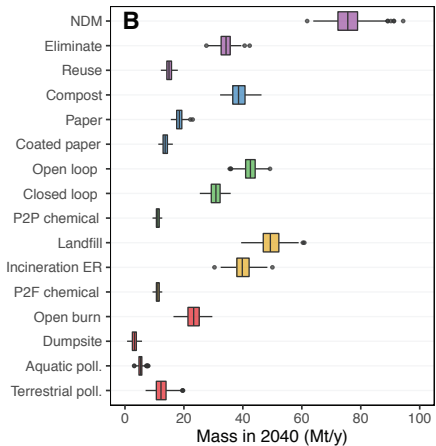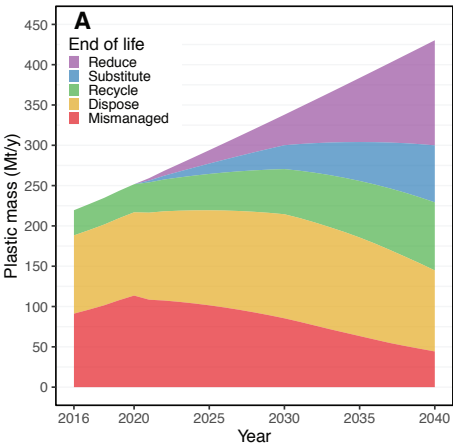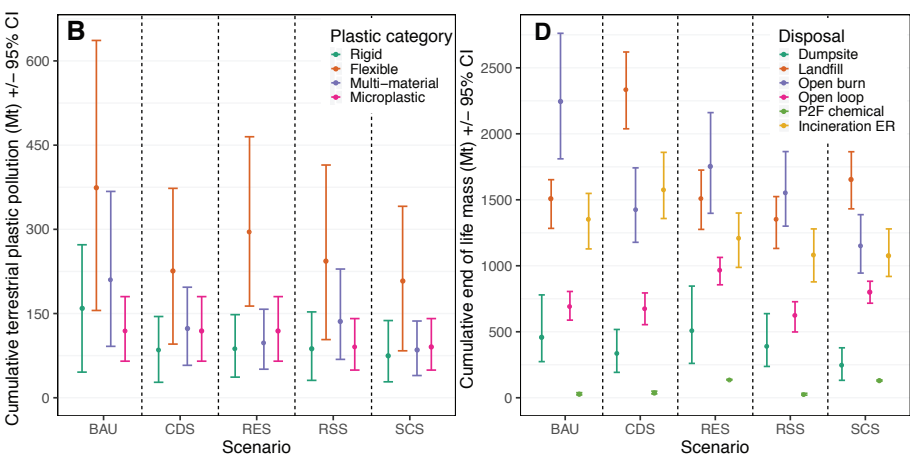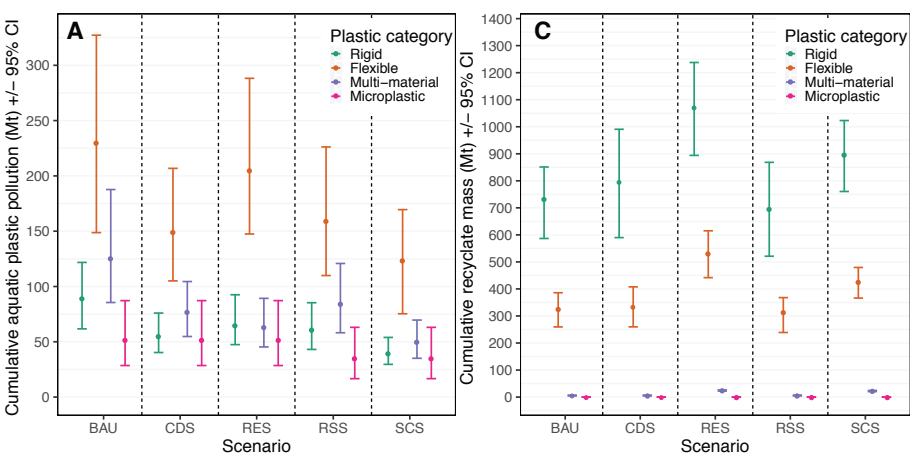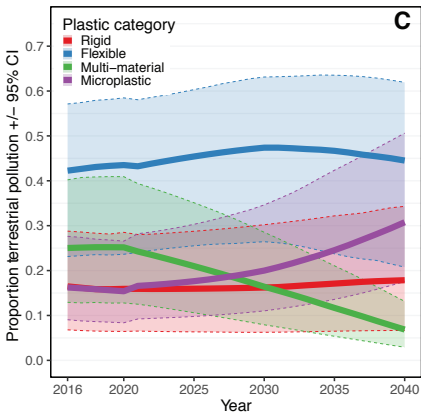
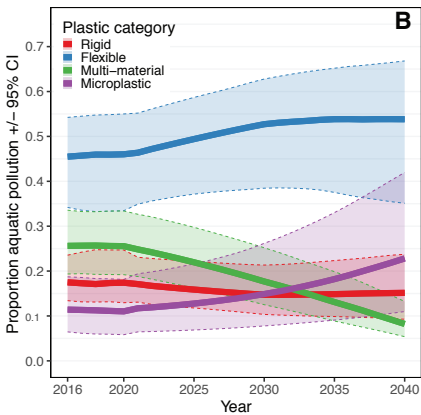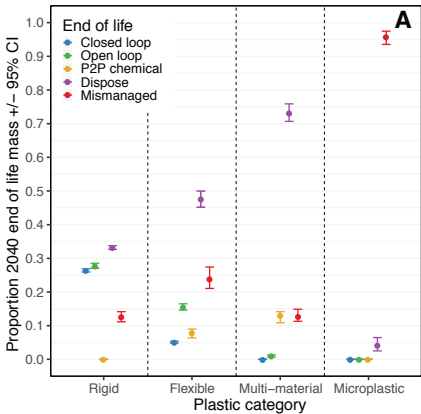PV net waste management costs, 2016−2040
(Billion 2018 USD, 3.5% discount rate) +/− 95% CI
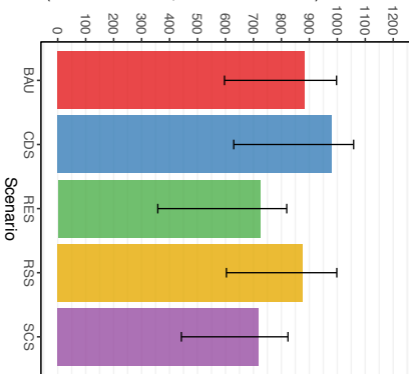
Table 1. Plastic mass; percent of total plastic demand under different end of life fates for year 2016 and for year 2040 under the 'Business as Usual' (BAU) and 'System Change' scenarios (SCS); and percent change in plastic mass under different end of life fates for SCS in 2040 relative to 2016 and BAU in 2040.

End of Life Fate	Plastic Mass (Mt/y) 95% CI			Fate as % Plastic Demand 95% CI			SCS 2040 % Change 95% CI	
	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 burn[*]	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.