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Supplementary Materials for

Evaluating Scenarios Toward Zero Plastic Pollution

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Materials and Methods

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1. Expert Panel

To evaluate the mitigation potential of various strategies for reducing plastic pollution from land-based sources, a comprehensive and representative model of the global plastic value chain was developed to analyze scenarios representing different proposed strategies. A panel of 17 experts, reflecting knowledge and experience throughout the plastic value chain and with broad geographic scope, was assembled to jointly develop a conceptual model of the global plastics value chain and inform scenario development (Table S1). In addition to working in plenary, the experts participated in smaller working groups to fully assess five different components of the plastic value chain. From July 2018 to July 2019, the panel participated in weekly to monthly working group calls and met at four in-person workshops (Table S2).

Expert panel consensus

Each working group developed the analytical and data framework for the relevant sub-sections of the plastic value chain. Where data were scarce or where insufficient scientific evidence was identified, the relevant working group members arrived at preliminary estimates through extensive discussion that were then presented to the entire expert panel in pre-workshop reading materials and validated by discussion in specific small- and large-group sessions at the in-person workshops. These estimates were finalized and agreed upon by consensus (whereby discussions continued until no dissent was voiced) for use in the analysis (hereafter, expert panel consensus).

2. System Maps

A system map was developed to conceptualize key stocks and flows of the global plastic value chain for macroplastics, including pathways that lead to land-based sources of terrestrial and aquatic (lakes, rivers and marine environments) plastic pollution (Figure S1). For the purposes of this analysis, we defined plastic pollution as the uncontrolled release of plastic waste into the environment resulting from ineffective management.

The architecture of this map was informed by the expert panel's collective knowledge of the global plastic system and iterated with ~50 experts from industry, government and civil society during a consultation process held in April – June 2019. The map aims to capture geographic and operational differences in waste flows at the global scale (see Figure S1, Section 3, and Section 10, respectively, for more detail).

The plastic value chain was categorized into five broad components to describe the various stages of plastic through its life cycle: production and consumption, collection and sorting, recycling, disposal and mismanaged waste. These components aligned with the expert panel's working groups (Section 1).

The production and consumption component covers the production and conversion of virgin plastic and recycled plastic feedstocks, plus any substitute materials introduced to deliver the same utility as plastics initially did. This component of the map also includes a sub-system map that evaluates the potential for reduction and substitution analyzed under some of the scenarios (Figure S2).

The collection and sorting component includes flows through formal and informal collection sectors that reflect waste management practices in different parts of the world as well as the global trade in waste (Sections 10 and 13). The recycling component differentiates the broad categories of existing recycling technologies that process different types of plastic waste (Section 11). The disposal component includes end of life waste management practices that safely dispose of plastic and ensure it does not leak into the environment (Section 12). The mismanaged waste component includes both point and non-point sources of plastic pollution to the environment (Section 14).

To evaluate the potential to mitigate microplastics pollution, sub-system maps of four key sources of primary microplastics (6) were also developed (Figures S3-S6 with details presented in Section 15).

3. Geographic Archetypes

Per capita waste generation and collection rates are correlated strongly with per capita gross national income (pcGNI) (49, 50) and gross domestic product per capita with purchasing power parity (pcGDPPP) (30). Formal recycling rates also correlate with pcGNI (51). The cost of collection, treatment, disposal and reprocessing, as well as waste management policy approaches and technological deployment, also vary with income category (50, 52). Per capita waste generation, collection costs and collection and processing rates correlate with population density (53).

Accordingly, we developed eight geographic archetypes based on income and population density to capture these geographic differences in plastic consumption, waste generation and post-consumption waste management pathways. Additionally, the amount of mismanaged plastic waste leaking into aquatic sources is correlated with the distance a population resides from a waterbody. To account for this effect, we defined two zones for a population's proximity to water.

To account for the effects of national development, each country was assigned to a per capita income category based on the World Bank classification scheme of low income (pcGNI < \$1,025), lower-middle income (\$1,026 < pcGNI < \$4,035), upper-middle income (\$4,036 < pcGNI < \$12,475), and high income (pcGNI > \$12,475), using FY2017 data (54). To account for the effects of population density, United Nations Department of Economic and Social Affairs (DESA) Population Division reports, including separation of population into urban and rural components from 2016-2040, (55) were to generate total archetype population. Together, these assignments resulted in eight geographic archetypes: (1) high-income – urban (HI-U), (2) high-income – rural (HI-R), (3) upper-middle income – urban (UMI-U), (4) upper-middle income – rural (UMI-R), (5) lower-middle income – urban (LMI-U), (6) lower-middle income – rural (LMI-R), (7) low-income – urban (LI-U), and (8) low-income – rural (LI-R) (55).

To account for the effects of proximity to water within each archetype, we estimated the proportion of each archetype's population living within one km of a river or coastal water using GIS. To do this, the 30 arc second resolution GPWv4 (55) 2015 population density map (56) was separated into urban and rural components according to European Commission definitions (i.e., where grid cells were defined as rural if they did not have a population density of at least 300 inhabitants per km^2 and a minimum contiguous population of 5,000 inhabitants). This dataset was then intersected with the 30 arc second HydroSHEDS river and coastline dataset (57), in which we defined rivers as those waterbodies with an upstream area of 25 km^2 or greater. As the HydroSHEDS dataset contains no data above 60°N latitude, population statistics for countries located either fully or partially above 60°N were estimated. In countries with partial coverage, national ratios were based on those areas of the country with HydroSHEDS coverage. In countries with no coverage, estimates were based on ratios of similar surrounding countries with coverage.

Table S3 presents the population for each archetype and zone used in model calculations.

4. Plastic Categories

4.1 Macroplastics

To estimate plastic flows through different post-consumption waste collection and management pathways, we defined three plastic categories relevant to municipal solid waste (MSW) systems: rigid monomaterial, flexible monomaterial and flexible multimaterial/multilayer. This differentiation is driven by the relative value recovery possibilities, supply and demand considerations and infrastructure requirements. For example, rigid monomaterial and multimaterial/multilayer have very different informal sector collection rates due to their inherent value and complexity (34, 58), and rigid (33) monomaterial and flexible monomaterial (59) have different recyclability profiles. These three plastic categories encompass numerous subcategories, with key product categories as follows:

- **Rigid monomaterials:** water bottles; other food-grade bottles; non-food-grade bottles; food service disposables; pots, tubs and trays; business-to-business (B2B) packaging; household goods; and other rigid monomaterials
- **Flexible monomaterials:** bags; monomaterial films; and B2B films
- **Multimaterial and multilayer:** sachets and other flexible multilayers; B2B multilayer packaging; household goods; sanitary items and diapers; and other multilayer or multimaterial

Thermosets and biodegradable plastics were intentionally excluded from our analysis. Thermosets are primarily used in the automotive and construction sectors and are therefore not a major component of MSW. Biodegradable plastics currently have a low production mass and are unlikely to grow significantly under a Business-as-Usual (BAU) scenario (projected to be less than 1% of plastic production by 2021) (60). Although not modeled as a separate plastic for the purpose of identifying unique waste collection and management pathways, compostable plastics were modeled as one possible plastic substitute (see Section 9).

4.2 Microplastics

In this study, we modeled the microplastic pool that first enters the environment in the size range of 1 µm - 5 mm (primary microplastics), compared with microplastics generated from degradation of macroplastic waste already in the environment. As the flow pathways of microplastics are different than those of macroplastics, microplastics were considered separately, and modeled using different system maps (see Section 15). Microplastic sources were selected for modeling based upon the availability of existing research, information on masses and the potential for modeling solutions. Four categories were modeled: tire abrasion (tire-wear particles, TWP; Figure S3), pellet loss (Figure S4), textile microfiber loss (Figure S5) and loss of microplastic ingredients from personal care products (PCP), including the full microsized spectrum of ingredients (6, 61) (Figure S6).

5. General Model Description

5.1 Overview and Choice of Approach

The Plastics-to-Ocean (P_2O) model is a data-driven coupled ordinary differential equation (ODE) model that calculates the flow of plastics through representative systems.

An ODE modeling framework was chosen for three main reasons. First, we are specifically interested in the flow rates of plastic, stocks of plastic held in the system, and in making accurate quantitative estimates of changes to these stocks and flows. Second, there are feedbacks in the system that complicate model dynamics, and the relationship of the modeled scenario forcings to the outputs cannot be learned from historical data. Third, the effects of discontinuities in forcing under some of the scenarios used, and the potential for flow constraints to be met in the model (causing secondary effects), mean that statistical models would not be able to account for the range of dynamics we see in the results.

Given these conditions and requirements, an ODE model is a natural choice, as their output is in the form of flows (derivatives) and stocks (integrals).

5.2 Plastic Flows

All model diagrams (Figure S1-Figure S6) show ‘boxes’ connected by ‘arrows’, representing plastic flows between various parts of the system. The numerical model simulates this flow of plastic between these various boxes, of which there are three types: 1) ‘plastic sources,’ representing the primary production of plastic, and plastic imports; 2) ‘pass-through’ boxes, which re-route flow to subsequent boxes; and 3) ‘plastic sinks,’ where plastic accumulates over time. Some of the flows are subject to constraints, which are defined below.

The model is formulated as a set of coupled differential equations, solved numerically, using software written in Matlab® (ver. 2017b) by Richard Bailey. Numerical integration is performed by the ODE45 (Runge-Kutta) algorithm, which provides solutions for instantaneous mass in each box at prescribed temporal resolution, from which the rates of flow can be calculated. Conservation of mass within the system is tracked as a measure of numerical accuracy, and the deviation is $<10^{-4}$ % in all cases, and typically $<10^{-8}$ %.

Each box has some combination of input and output flow(s), and its change of mass is the difference between these summed inputs and outputs.

$$\frac{dM_i}{dt} = \sum F_{in}(t) - \sum F_{out}(t) \qquad \text{Eq. (1)}$$

where M is instantaneous mass (metric ton [t]) in box i, t is time, and F is the flow rate (t/yr). The summations are not explicit here and apply to all relevant in/out flows. Note that each F is a function of time, and that several different formulations are used for both the macro- and micro-plastic models, as outlined below.

First, the nth flow from box j can be defined as a proportion of the available mass in box j:

$$F_{j,n}(t) = M_j(t).R.P_{j,n}(t) \qquad \text{Eq. (2a)}$$

where $P_{j,n} \in [0,1]$ is the proportion of the total flow from Box j. $P_{j,n}(t)$ can be defined as a continuous function ($P_{j,n}(t) = f(t)$), or as an arbitrary timeseries which is interpolated at t as required. R is an arbitrary large positive scaling constant that affects the rate at which plastic is 'processed' through the box but does not change the equilibrium flow itself. A relatively high value of R ensures flows are sufficiently fast that the system reaches equilibrium relatively quickly (< 0.1 year), and that transient (instantaneous) masses are relatively low in all but the 'sink' boxes (i.e., those with no outflows). A value of 100 was used in all simulations.

Second, in the case where there are N flows from box j, a flow can be defined as a 'plug' flow, a residual to the other N-1 proportional flows (as defined Eq.2a). Hence,

$$F_{j,n}(t) = M_j(t).R.\left(1 - \sum_{\forall x \neq n} F_{j,x}(t)\right)\beta_{j,n} \qquad \text{Eq. (2b)}$$

In cases where multiple residual flows exist, the proportion attributed to each is controlled by $\beta_{j,n} \in [0,1]$, so preferential flow to multiple targets can be achieved (with $\sum_r B_{j,r} = 1$, where r indexes the residual flows).

Third, flows can be defined in absolute terms:

$$F_{j,n}(t) = min\left(M_j(t).R,\ K_{j,n}(t)\right) \qquad \text{Eq. (2c)}$$

where $K_{j,n}(t)$ is either a separate continuous function ($K_{j,n}(t) = f(t)$), or an arbitrary timeseries which is interpolated at t as required. The $min(\cdot)$ is included so a prescribed absolute flow cannot exceed the mass available.

Residual flows can also be used when other flows are defined in absolute terms:

$$F_{j,n}(t) = \left(M_j(t).R - \sum_{\forall x \neq n} F_{j,x}(t)\right)\beta_{j,n} \qquad \text{Eq. (2d)}$$

Mixtures of all of these flow types can used for any box, and this is handled by the software.

5.3 Constraints

A variety of different constraints can be applied in the model, which control both flows and masses within the system, all of which can be applied over specified time windows. Many of the flow and mass capacity constraints are not known a priori but are required in order to apply the necessary constraints under future scenarios. To solve this problem, the model is run to equilibrium without constraints under the baseline conditions of year 2016 (equilibrium under constant forcing conditions is reached on the order of weeks of model time). The model flows, and the masses in each box, are then used as baseline values from which to calculate subsequent constraints as necessary (under the assumption that capacity was met in year 2016) and provide the initial conditions for the model runs described, covering the period 2016-2040.

Mass constraints

Constraints on the amount of mass held in any box are necessary in some cases, and these are defined by G_j, the baseline mass (t) observed in the equilibrium model run; c, the capacity growth rate; and z, a multiplying factor to account for the additional capacity beyond the exact equilibrium conditions (here set to 1.02).

In cases where the box is a finite sink (e.g., landfill), and there is compound growth in capacity ($c > 0$), capacity (g) is defined:

$$g_j(t) = G_j + \left(\frac{G_j}{c_j(1+c_j)}\right) z_j\left(1 + {c_j}^{\lfloor t \rfloor + 1}\right) - \left(\frac{G_j}{c_j(1+c_j)}\right) z_j\left(1 + {c_j}^{\lfloor t \rfloor}\right) \qquad \text{Eq. (3a)}$$

In the case of a sink with c=0, capacity simply grows in multiples of the model year number:

$$g_j(t) = G_j z_j + \lfloor t - 1 \rfloor . G_j \qquad \text{Eq. (3b)}$$

If a constraint on a finite sink is reached (i.e. if mass reaches the limit calculated), flows into that box are set to zero, and it accepts no more mass until additional capacity is made available (possibly in the following year of simulation). This affects all upstream boxes, which are (by definition) not finite sinks but ‘flow through’ boxes. The instantaneous mass of each upstream box will increase, meaning any relative flows out of those boxes will increase. However, if flows from those upstream boxes are constrained, this may cause mass to accumulate in those boxes (flow constraints are described below). Mass accumulation in flow-through boxes is not desired behavior in the model, as this does not reflect real-world behavior (if the output from notional process ‘A’ is rate-limited, mass should not accumulate at the location of process ‘A’ due to an excess of inputs). Rather, once process ‘A’ has accumulated sufficient mass to maintain its annual output rate for the remainder of the current year, it accepts no further mass. The threshold for halting inputs to a box is:

$$M_j^*(t) = g_j(\lfloor t \rfloor + 1).(1-\alpha).\left(1 - (t - \lfloor t \rfloor)\right) + g_j(t_0).\alpha \qquad \text{Eq. (4)}$$

where $\alpha \in [0,1]$ provides a buffer that allows a prescribed proportion of mass accumulation and is set equal to 0.05 in all simulations. Then if $M_j^*(t) \geq M_j(t)$, box j accepts no additional plastic for the remainder of the year, and all flows to that box are set to zero (then affecting potential mass accumulation in upstream boxes).

Other outflow constraints

The absolute flow rate of any flow can be capped at a maximum value, within a defined time window. If this limit is reached, additional flow is naturally routed to the other outflows (if present) as less mass is removed by the capped flow than would otherwise be the case. Constraints can also be set on the total flow from a box (summed over all outflows). These are defined by the baseline flow rates observed in the equilibrium model runs, summed over outflows from each box; d, the capacity growth rate; and y, a multiplying factor to account for the additional capacity beyond the exact equilibrium conditions.

$$F_j^*(t) = \left(\sum_n F_{j,n}\right) y_j \left(1 + d_j{}^{\lfloor t \rfloor}\right) \qquad \text{Eq. (5a)}$$

Then, if calculated outflows $F_{j,n}(t) \geq F_j^*(t)$, the outflows from box j are scaled as

$$F_{j,n}^{scaled}(t) = \left(F_{j,n}(t).F_j^*(t)\right) \Big/ \sum_n F_{j,n} \qquad \text{Eq. (5b)}$$

which maintains the flow proportions. Consequently, the instantaneous mass within box j increases.

5.4 Special Cases

Three ad hoc special cases were used in the modeled macroplastic system to account for situations where several factors that may attenuate flow and constraints may differ depending on the scenario modeled:

i. Plastic mass collected by the informal sector (arrow B2): We did not assume that waste collection by the informal sector is a direct fraction of total plastic waste generated because plastic waste generation differs significantly between scenarios and it seemed unreasonable to assume that the size of the informal sector will grow/shrink linearly, given that they collect many other things, not just plastic. We therefore added the projection of total waste-picker population as one of the factors influencing arrow B2. Underlying assumptions and reasoning for the initial flows A1 (collected plastic), A2 (uncollected plastic), B1 (formal collection) and B2 (informal collection) are described in Section 10.1 and 10.2. Values for these flows were key differentiators among scenarios and were provided as a timeseries of absolute values instead of scaling linearly with input flows. Values were provided as described for (Eq. 2c) and interpolated over time as required for integration.

ii. Projected feedstock flow for chemical recycling (arrow E1): We assumed that chemical recycling flows were constrained by two factors: 1) the amount of relevant feedstock available for chemical recycling (by geography) and 2) the speed at which chemical recycling infrastructure could be built. In some scenarios the former was the limiting constraint while in others it was the latter. The model applied the relevant constraint based on the amount of feedstock and the infrastructure capacity available in a given scenario. Flow E1 (mixed collection to chemical conversion) was constrained to be no higher than 50% of the total flow from Box C (formal collection) and also no higher than the baseline flow growing at a compound rate of 16.5% from 2021.
iii. Plastic waste collected from dumpsites by the informal sector (arrow V1) for rigid monomaterial plastics: We assumed the number of waste pickers collecting plastic from dumpsites was relatively stable across different scenarios and therefore, treated V1 as a model input, rather than model output. We therefore gave flow V1 precedence over other flows from Box V (i.e. other flows from Box V share the residual of the input to Box V once flow V1 has been satisfied, and if the input to Box V is less than the prescribed flow for V1 (which did not occur during any simulation), V1 takes the entire input to Box V and other flows are set to zero).

5.5 The Global Plastic System

Individual model runs were conducted for each combination of geographic archetype, population zone and macro- and microplastic type. Results were aggregated across population zones within scenario and plastic types to obtain archetype values. Archetype values were then summed within scenario to obtain global values.

5.6 Uncertainty

All model inputs are associated with uncertainty, and this uncertainty is propagated through to the model output using a statistical re-sampling of the inputs over an ensemble simulation (Monte Carlo, MC, simulation). The width of the uncertainty on each input variable is defined by a data pedigree and the resultant variation in plastic flows and masses is propagated naturally throughout the MC simulations. Uncertainties related to costs are computed using an additional MC step using parameter uncertainties assigned using the same pedigree system. A total of 300 MC simulations were carried out for plastic flows; 500 were performed for costs.

Pedigree Framework for Uncertainty:

Due to the variability of data availability, quality and uncertainty characterization throughout the plastic system and across geographic archetypes and plastic types, uncertainty on all input variables were standardized across all data using a data pedigree scoring framework. For each input variable calculated, all data sources used were scored across a four attributes matrix (Table S4). The scores for each row of the matrix were then summed to yield a total pedigree score.

Application of Uncertainty:

Pedigree scores for each data source were placed into pedigree categories, with each category assigned an uncertainty (Table S5). Uncertainty values represent the upper and lower boundaries of a uniform distribution centered around a mean central value. For each variable, uncertainty was assigned according to the lowest-quality data source used in the calculation of a mean value.

The highest quality bin of data was assigned an uncertainty level of ± 10%. The magnitude of this relative error was assigned through identification of the variable in the analysis with a large number of high-quality data sources – specifically, the removal efficiency of wastewater treatment. By default, expert opinions and expert consensus were assigned to data pedigree level 4 - the highest level of uncertainty. The pedigree assigned to each input is shown in Table S6.

5.7 Sensitivity Analysis

One-at-a-time sensitivity analysis was performed to assess the dependence of each (target) flow, and each of the calculated economic outcomes, on each (driving) flow within the macroplastic model, and for the microplastic flows of the TWP model, which accounted for the overwhelming majority source of microplastic. Calculations were performed under the BAU scenario, for year 2 of the modeled period, to avoid time-dependence in the results from 2020 onwards.

For macroplastic, the definitions of the modeled mass flows are defined in a variety of ways (as time-dependent functions, proportions of upstream flows, prescribed absolute values and as residual ‘plug’ flows). Accordingly, it is not possible to capture the dependencies of the system using only the parameter inputs. Instead, driving flows were scaled, one at a time, by 0.95, 1.0, 1.05, in three successive models runs. No such scaling was performed for ‘plug’ flows, as these can be calculated as complimentary to the non-plug flows. The gradient of resultant against driving flow then defines the sensitivity. This can be extended to composite target flows, such as the total flow to aquatic systems, and calculated in the same way. This analysis allows calculation of, for example, the required change in any flow within the system in order to reduce total plastic pollution flow by some arbitrary amount. As costs are also calculated, this analysis can be extended further to calculate the system-level profit, costs or required investment, for example, per ton of reduction in aquatic or terrestrial pollution due to intervention in any relevant part of the system. The sensitivity of aquatic plastic flow to total plastic input (hence the effect of reduce and substitute interventions) was calculated directly from the model outputs, assuming for marginal changes in total plastic input, the ratio of aquatic plastic pollution to input remained constant.

Calculations for microplastic sensitivities are simpler to calculate because the microplastic systems are linear (i.e., no feedbacks in the system maps), so changes in, for example, total flow to the aquatic environment can be calculated directly from the total system inputs and the flow proportions. No economic analysis (or therefore economic sensitivity analysis) is included in the microplastic modelling.

6. Scenario Construction

To understand the current trajectory of the plastic system leading to plastic pollution (baselines), we built BAU, as well as CCS to capture the commitments that have been made by governments and industry between 2016 and 2019. In addition to these two baseline scenarios, we constructed four solution-oriented scenarios to represent alternative strategies for reducing environmental plastic pollution from land-based sources: CDS, RES, RSS, and SCS.

To construct the solution scenarios, we first conceptualized four classes, or “wedges,” of system interventions: reduce, substitute, dispose and recycle. We then defined eight primary categories of interventions that impact one or more of the four wedges (Table S7). The eight interventions reflect the solutions that exist across the entire plastic value chain, where each represents a distinct approach that can be taken to prevent plastics from flowing into the terrestrial or aquatic environment. Each intervention encompasses multiple components that can collectively contribute to the overarching objective (e.g., reducing overall plastic in the system includes both elimination and reduction through reuse models).

We parameterized three sets of values that were used in combination to construct each scenario (see Table S8): baseline conditions (BL) under BAU, assessment of future implementation of government and industry commitments and maximally foreseen assessment (MFA) of the implementation or growth rates of each system intervention.

The framework for specific parameterization of each stock and flow for the scenarios are detailed in Table S8. These estimates were based on historical trends, learning curves for new technologies with similar characteristics, industry expert assessment, expert panel consensus and a feasibility assessment framework of innovative business practices and new material substitution. Methodologies for estimating these three sets of values are detailed in the remaining sections of this document (i.e., Sections 7 – 15) below.

We constructed the four non-BAU, non-CCS scenarios around relevant interventions in various combinations applied to the BAU scenario (Table S8).

7. Total Macroplastic Input into the System

We used MSW data from the World Bank's What a Waste v2.0 dataset (62) to estimate the total land-based macroplastic input into the system with the potential to enter aquatic and terrestrial systems as plastic pollution. MSW includes the predominant land-based plastic waste categories found in ocean plastic waste characterization studies (e.g., packaging, single-use products, toys, cigarette butts, consumer durables and household and institutional products) and excludes the plastic products not typically found among these studies (e.g., industrial and agricultural plastic waste; medical, hazardous, electronic, construction, bulky items; and automotive waste [waste streams typically handled and regulated separately]) (63–67). MSW plastic also excludes the plastic portion of textile, shoe, carpet and furniture waste, as they are not reported as plastic in MSW reporting.

Definitions and classifications of MSW are not consistent among countries (68), and therefore, the categories of waste reported in waste data vary. For example, some countries include construction and demolition waste in their reported MSW data while others do not (30). The World Bank's What a Waste 2.0 dataset (19) represents the most comprehensive and consistent global dataset available on MSW, and any variations among countries in the composition of reported waste would be smoothed out at the archetype level.

We estimated total macroplastic waste generated (m_{PG}) for each archetype using UN population data by archetype, 2016 m_{PG} by country (53) and projected growth rates of plastic generation (69).

7.1 Population

Population by archetype data are from the United Nations (55), which were used to calculate archetype-level compound annual growth rates (CAGR) (Table S10).

7.2 Annual Total Plastic Waste Generation by Archetype

The World Bank reports aggregate waste generation and percent plastic of MSW (% plastic) at the country level (30). As waste management logistics and economics differ between urban and rural contexts, total plastic waste generation was divided into urban and rural fractions.

We first derived the 2016 plastic waste generation by country using the World Bank's What a Waste Dataset (70). Where % plastic by country was not reported, we used a weighted average of % plastic for countries in the same World Bank income group in the same region (e.g., for Burundi, we assumed % plastic derived from the weighted average of % plastic from other low-income countries in Sub-Saharan Africa). The weighted average of the income group was also applied to countries that reported % plastic below 5% based on the knowledge and experience of our expert panel.

To project total annual plastic waste generation to 2040, we applied a year-on-year plastic growth rate to the 2016 plastic waste figure. Growth rates were calculated using plastic waste projections (71) at a regional scale, which assumes that per capita waste generation increases with per capita income and stabilizes at 120 kg plastic per year at a per capita income level of USD 40,000. We converted these regional growth rates into our archetypes using World Bank regional groupings – HI included 100% of NAFTA, 100% Developed Asia, 64% Europe, 17% Middle East, 6% China and 15% Latin America (53). Each country's 2016 plastic waste generation was then multiplied by the respective income category growth rate.

Using the estimated national plastic waste generation projections (2016-2040), we derived per capita figures split between urban and rural population per country. We partitioned total plastic waste generation by urban and rural contributions assuming ratios on the relative generation of urban and rural residents as follows: HI 1:1, UMI 1.5:1, LMI 2:1, LI 2:1 (53). Combining the urban-rural waste generation ratio with respective urban-rural population ratio, we estimated the per capita plastic waste generation for rural and urban populations by country. To arrive at archetype total annual waste generation, we aggregated the respective country-level, urban-rural plastic waste generation for 2016-2040 from projected per capita waste generation and population data (Table S11).

8. Plastic Categories as a Proportion of Total MSW Plastic

We allocated total waste input among three macroplastic categories using 2016 data.

For the two high income archetypes (HI-U and HI-R), proportions were assigned based on waste characterization data from the United Kingdom (UK) (72–75), which was the most comprehensive country-level dataset available and distinguished between rigid, flexible and multimaterial waste types.

The suitability of the UK data to represent the HI archetypes was assessed in two ways. First, the average plastic packaging waste per capita for the UK in 2016 was compared to that of the EU28 and found to be similar (34 kg vs. 32 kg) (76).

Second, the UK waste composition data were compared to available data from the USA (77), the largest producer of waste in the HI archetype. After adjusting for differences in plastic composition and reporting categories, the comparison showed that the USA has a higher percentage of durable plastics in MSW. The USA has one of the highest amounts of waste generation per capita in the world, annually generating 737 kg per person compared to a total OECD average of 519 kg and an OECD-Europe average of 480 kg (68). If durable goods are excluded, US and EU waste composition data showed a strong similarity, with 34-45% more rigids than flexible/multilayers.

Detailed waste composition studies were found for five LMI nations, including publicly available data from the Philippines (78) and proprietary waste composition data from Cote D'Ivoire (79), India (80), Vietnam (81) and Indonesia (82). These data were averaged to estimate archetype-level waste streams (Table S13). Unfortunately, product applications reported in these data were not consistent with the detailed categories reported from the UK, making direct comparisons impossible. Accordingly, we assumed that the proportion of product applications within plastic type was identical across all income categories, with one exception. Waste composition data indicate that the composition of the multimaterial/multilayer plastic type category differed significantly in lower- and middle-income countries from that of HI archetypes, with "sachets and multilayer flexibles" making up an average of 18% of total waste in the former, but only 4% in HI. Therefore, sachets and multilayer flexibles were allocated at 18% for LMI. To allocate the other product applications, the percentage of diapers (2%) was determined from the LMI data, and the remainder was split between laminated paper and aluminum and household goods as per the HI proportions (Table S12) (79–83).

Waste composition studies could not be found for countries with LI or UMI economies. However, expert panel consensus concluded that the mix of plastic product types was similar among LI, LMI and UMI countries, which were therefore assumed to be identical in the model. Although it did not contain the details necessary to be included in allocating plastic waste to our three plastic types, one study in Brazil found that rigid plastic waste represented 34% of plastic mass in the MSW stream (84). This value is nearly identical to the 33% average obtained from our LMI waste composition data, suggesting that our assumption of identical waste streams across LI, LMI and UMI archetypes reflect available data.

Across all archetypes, we allocated waste composition to the three modeled plastic types according to values presented in Table S13 and Table S14.

Data on the proportion of rigid to flexible PVC were unavailable. PVC makes up only 0% - 2% of MSW; we assumed a 50-50 split between rigid and flexible PVC.

The proportion of MSW allocated to each plastic type is shown in Table S15. We assumed these percentages change under BAU following the 2014-2019 trend of a decrease in share of rigid monomaterials of 0.22% CAGR per year and an increase in share of flexible products at 0.11% CAGR per year (85).

9. Reduce and Substitute

Reduce and substitute interventions were not applied to the BAU scenario. The methodology used to estimate current commitment values and MFA values are described below.

9.1 Current Commitments for Reduce and Substitute Interventions

Modelling of current commitments includes both the reduction in plastic resulting from government policies as well as the reduction committed by industry through the New Plastic Economy (NPEC) Global Commitments (86).

We estimated the potential reduction in plastic resulting from government bans/levies that have been passed into legislation, but which have not been fully implemented.

The UN Single Use plastic report (87) was used to develop a comprehensive list of bans and levies. The focus was on national level policies, including the EU regional level, as opposed to local policies in order to avoid double counting. High-level strategy documents or future policies that had been announced but are not yet passed into legislation were also excluded. Our analysis included only commitments on inputs (e.g., actions stakeholders have control over such as levies and bans), and not on outputs/targets (e.g., stated future goals for % reduction in leakage). A total of 89 national/regional reduction policies were quantified.

Effectiveness of policies

Two types of policies were included: levies and bans. A ‘policy effectiveness factor’ was applied per type of policy using the UNEP report (87) as guidance. For bans, we assumed 100% effectiveness for all archetypes. For levies, the impact effectiveness of HI was 69% as reported in (87). This percentage was applied to reported data points less than 69% (88) or missing.

European Union Single-Use Plastics Directive

The EU Single-Use Plastics Directive (26) was separately analyzed to determine its plastic reduction impact. First, the products included in the EU plastic ban were identified, and then the analysis conducted by Overbrook (88) was used to estimate the relative proportion of food service disposable plastic that was targeted by the EU plastic ban. In addition to this reduction, we also made the assumption that 100% of bags would be eliminated. For countries within the EU that already had a ban or levy in place, the reduction of plastic was assumed to increase to be in line with the EU directive from 2021 onwards.

Mass reduction calculation

We mapped the plastic policies to the targeted products, either as bags or food service disposables (FSD). Bags were mapped as flexible monomaterials, while FSD were mapped as rigid monomaterials. We then assigned likely policy effectiveness rating to each policy as described above. We calculated the total weight of plastic affected by the policy by multiplying (a) the individual country’s total MSW plastic weight by (b) the corresponding proportion that the bags or FSD represents in that archetype income level (Table S14) and then by (c) the policy effectiveness rating.

NPEC Global Commitment were analyzed to estimate the potential plastic reduction resulting from the commitments made by its' signatories in three separate ways:

1. Increase in recycled content

NPEC commitment to increase recycled content signals a demand in recycled feedstock, the effect of which was modeled as an increase in collection in order to fulfill this demand. Please see Section 10.3 for further detail.

2. Reduction of plastic in line with commitment to "take action to eliminate problematic or unnecessary plastic packaging by 2025"

In order to estimate the reduction in plastic, we used Unilever’s explicit target. Unilever’s reduction of 100,000 t of plastic packaging by 2025 over its current volume of 700,000 t translates into a reduction of 14% (86). Unilever’s reduction of 100,000 t of plastic packaging by 2025 over its current volume of 700,000 t translates into a reduction of 14% (86). Unilever’s target is seen as ambitious among the signatories. As a result, we made the assumption that the levels of reduction by other signatories would be in the range of 7.5% This reduction was applied to the 20% of the global plastic packaging market share represented by NPEC signatories.

The resulting 1.5% reduction was then applied to the proportion of plastic that corresponds to packaging only and kept constant from 2025 to 2040 (Table S16).

To ensure we did not underestimate the impact of current commitments, this reduction is modeled as an absolute elimination (box 0.1), even though a proportion might be a reduction in plastic through the increased adoption of NDM.

Finally, these figures are added to the calculated reduction of plastic due to government bans and levies. To be conservative, no overlap was assumed, and the reductions were combined.

3. Innovation *“to ensure 100% of plastic packaging can be easily and safely reused, recycled, or composted by 2025”*

In order to model this commitment, we modeled a shift from multimaterial to monomaterial flexible plastic for the proportion that corresponds to packaging. This was applied to 20% of the volume, to represent the global plastic packaging market share represented by NPEC signatories, across all archetypes (Table S18).

Our estimates likely represent an underestimate as they did not include potential growth in informal collection or an increase in formal segregated collection across all plastic types. With more recyclable plastics in the market, this is expected to happen.

9.2 MFA for Reduce and Substitute Interventions

We developed a framework to assess the maximum potential for reduction and substitution of plastic utility demand, Box ‘0’ in the system maps (Figure S1 and Figure S2), to model Interventions I and II (Table S7) in the RSS and SCS scenarios (Table S8). This framework, as detailed in the sections below, consists of a three-step process: (1) MSW data were categorized into 15 product applications and the three plastic categories (see Section 4.1); (2) the maximum potential level to which BAU demand (Box '0') could be reduced (Box 0.5) was calculated by applying three 'reduce' levers (Box 0.1, 0.2, 0.3) to each product application; and (3) the maximum potential level to which the remaining utility demand (Box 0.4) could be substituted by non-plastic materials (Box 0.7) was calculated, modelling three substitute materials (Box 0.9, 0.10, 0.11). The residual utility demand, including both single-use and multi-use plastic (Box 0.8), connect back to the main system map (Figure S1) via Box A.

For Intervention I, we modeled three levers – eliminate, reuse at the consumer level, and reuse at the commercial level) (Table S19). For Intervention II, we modeled three levers around three potential materials for substitution (Table S19). These three substitution materials (paper, coasted paper and compostables, as shown in Table S19were selected, as they are the most prevalent substitutes available today for replacing "problematic" plastics - films and multilayer flexibles, which have low recycling rates and a high leakage rate into the environment, particularly in LI and LMI countries. We did not model single-use glass, aluminum and laminated cartons, which are possible substitutes for rigid monomaterial plastics, as they can have higher life-cycle GHG emissions compared to rigid monomaterial plastics, but may perform well from a GHG perspective where they have a high collection and recycling rate compared to plastic or where supply chains are shorter.

Categorization of MSW data by product application and relevance to reduction and substitution levers

We categorized MSW data into 15 plastic product categories with similar utility, which we categorized into the three plastic categories – rigid monomaterial, flexible monomaterial, or multimaterial/multilayer (Table S20). We then assessed the applicability of each reduction and substitution lever to the plastic categories based on existing businesses, policies, available technologies, environmental trade-offs and consumer trends observed to date (Table S20).

Application of reduce and substitute levers: Limiting factors

We applied the reduce and substitute interventions hierarchically to the MSW product applications. We first assessed the maximum potential level (as a percentage) to which BAU demand could be reduced (Figure S2, Box 0.5) for each product application through the three reduce levers (Table S19). We then assessed the substitution potential (Box 0.12) of the residual plastic with three substitute materials (Table S19).

To assess the reduction or substitution potential of each product application, we developed a limiting factor scoring framework. This framework assesses four attributes related to the feasibility of a product application for plastic reduction or substitution: technology readiness level (TRL), performance, convenience and cost (Table S21). Each product application was scored on a scale of 1-4 (with 4 representing the most feasible option) against the four attributes based on expert panel consensus. The potential impact of policy intervention is not explicitly reflected in the framework. However, it was considered as an enabling factor in the assessment of the limiting factor score as it can accelerate TRL development and impact on the technology, cost, performance or convenience of an alternative material or delivery model. It may play a role in changing the limiting factor scores over time.

For each reduce lever, the overall limiting factor level for a product application was determined (limited) by the lowest score among the four attributes (Table S22). As such, the limiting factor score can be considered conservative; all four attributes were weighted equally but some may play a greater role in different geographic archetypes, according to income levels, culture and lifestyle, or may be altered by new policy. We assumed that HI archetypes have a different overall limiting factor score compared to the other three archetype income levels, and that the same overall limiting factor level apply to urban and rural archetypes within an income level.

For the substitute levers, the overall limiting factor level, “overall substitutability,” for each product application was defined as the limiting factor score of its best-rated substitute material (Table S22). This process was used to avoid over-estimation, as it was assumed the possible speed of substitution away from plastic reflects the overall penetrability of the plastic-dominated market dynamics and the suitability and availability of all new materials, rather than each material alone. We made assumptions about the allocation of plastic mass substituted among the three modeled substitute materials based on their relative scores (Table S23). Scoring was assessed separately for the HI archetype and the UMI, LMI and LI archetypes by expert panel consensus (Table S22). For a given score, it was assumed the speed of substitution uptake is the same for all archetypes.

Application of reduce and substitute levers: Future market reach

For each overall limiting factor score level, we assessed a potential market reach in 2030 and 2040, based on expert panel consensus informed by the speed of historical socio-technological shifts of similar technologies, business models and policies (Table S24).

An overall limiting factor level of 4 reflects the existence of available technologies that meet or surpass the requirements of consumers and can be produced and distributed at scale, providing a net savings or comparable cost. Historically, quick adoption of these models by society was achieved through well-defined policy objectives. For example, the phase out of ozone depleting substances, particularly chlorofluorocarbon (CFC) compounds, was aided by the existence of acceptable substitutes and the adoption of the Montreal Protocol. This combination led to a 96% decrease of controlled ozone-depleting substance emissions globally within 20 years from 1.32 million ODP tons in 1989 (the first year of records in the UNEP dataset) to 0.05 million in 2009 (89). This policy had an unusually successful global uptake, so we assumed a more conservative global market penetration rate of 80% in 2040 and 50% in 2030 accordingly.

An overall limiting factor level of 3 reflects technologies or business models that are not yet at commercial scale, do not meet all performance requirements of the consumers and/or will require additional infrastructure to scale. Overall, their adoption is limited by consumers or wider supply chains. For example, based on desk research, Compact Discs, were in TRL 5-8 in approximately 1978, which we would attribute a limiting factor level of 3. Within 10 years of this date they had scaled to 20% of the market in the USA (90), despite being more durable and having higher storage capacity than its competitors due to the fact that they could not be used with existing music players, imposing a cost to consumers to purchase a CD player and hindering more widespread adoption. Within 20 years they had reached 80% of music sales (90), but this could be considered a best-case scenario of market uptake and would not reflect average uptake. To be conservative we assumed a market penetration rate for the limiting factor level of 3 at 50% in 2040 and at 20% in 2030 accordingly.

An overall limiting factor level of 2 reflects technologies or business models in their nascent stages with limited functionality, high prices and convenience only to a niche consumer base. For example, based on desk research, the foundations of the white LED light were developed in approximately 1994, the equivalent of TRL 1-4 or a limiting factor level of 2. It had a longer lifetime than its competitors and could provide consumers net savings if used effectively. However, high prices and poor performance led to its adoption only by eco-conscious consumers. Twenty years later in 2014 they had reached a global market uptake of 11% (91). We assumed a market penetration rate for the limiting factor level of 2 at 10% in 2040 and 1% in 2030 accordingly.

Application of reduce and substitute levers: Plastic utility and mass reduction

We used the maximum potential market penetration rate to calculate the resulting reduction in plastic mass requirements for each product application and then aggregated to each plastic category.

We applied the reduce and substitute levers in a hierarchical order: (1) “eliminate,” (2) “reuse – consumer,” (3) “reuse - NDM,” and (4) “substitute.”

Singles-use plastics

Single-use plastic within our model is a term to distinguish all plastics that are not reused as part of the “reuse – consumer” or “reuse – NDM” levers. For example, under BAU, 100% of plastics would be considered single-use. For single-use plastic, the residual plastic utility/mass after reduction and substitution levers were applied was calculated for each product application as follows:

$$m_{P,RS} = m_{PPA,year} \times [(1 - LF_E) \times (1 - LF_{RC}) \times (1 - LF_{RNDM}) \times (1 - LF_S)] \quad \text{Eq. (6)}$$

where

$m_{P,RS}$ is the residual plastic mass after the reduce and substitute levers have been applied;
$m_{PPA,year}$ is the plastic mass for a specific product application for a specific year (2030 or 2040);
LF_E is the limiting factor % market penetration for elimination;
LF_{RC} is the limiting factor % market penetration for reuse - consumer;
LF_{RNDM} is the limiting factor % market penetration for reuse - NDM; and
LF_S is the limiting factor % market penetration for overall suitability of substitution.

Multi-use plastics

For multi-use packaging, we calculated the mass of plastic waste that was generated from multi-use packaging in the “reuse – consumer” and “reuse – NDM” levers as follows. Multi-use plastics were only considered to derive from non-food application multi-use packaging. For multi-use food packaging application, we assumed that this application would be completely substituted by existing materials, e.g., glass, metal and fiber-based packages that may be more suitable for food safety. To calculate the resulting multi-use plastic mass, we used a "Waste Ratio," which reflects the mass of reusable products which be manufactured to deliver the equivalent utility of a kg of single-use plastic. For the reuse – consumer lever, only the plastic bag product application involved multi-use plastic; therefore, a Waste Ratio of 58% was used; for the reuse – NDM lever, an average Waste Ratio of 12% was used (for Waste Ratio calculations, see Section 16.2). In the case where a product application includes both food or non-food contact packaging, we assumed that 33% was for non-food contact. This percentage was based on the total percentage of grocery packaging that is used for food in the UK (75). Similarly, we assumed multi-use plastic mass did not arise from diapers, wet-wipes and sanitary pads because no commercial, re-usable plastic alternatives currently exist for these items (Table S25).

For each plastic category, we summed the single-use plastic $m_{P,RS}$ for all product categories under that plastic category and added any multi-use plastic mass to arrive at the mass of plastic for that plastic category in Box A. We converted this mass going into Box A to the MFA for reduce and substitute potential for the total plastic mass in Box A by dividing the sum of $m_{P,RS}$ and multi-use plastic mass for each plastic category in 2030 or 2040 by the respective BAU mass.

10. Collection and Sorting

10.1 Collection Rate (Arrow A1) and Collected Mass (Box B)

We defined plastics 'collection rate' ($\%CR_P$; Arrow A1) as the proportion of the mass of waste plastic generated (m_{PG}, weight as received [wt. ar]; Box A) that is collected (m_{PCol}; wt. ar; Box B) over one calendar year, n (Eq. 7). For all masses used in this analysis, it is assumed that they represent the weight of the waste 'as received' (wt. ar.).

$$\%CR_P = \frac{m_{PCol}}{m_{PG}} \times 100 \qquad \text{Eq. (7)}$$

BL and MFA values are shown below. No commitments to alter collection rates were found.

BL:

For the base year 2016, we took the $\%CR_P$ values as reported by Kaza et al. (30) (Table S26), and we assumed that m_{PCol} is equal to the entire collected mass of plastic waste generated in MSW (Eq. 8).

$$m_{PCol} = \%CR_P \times m_{PG} \qquad \text{Eq. (8)}$$

As plastic waste generation (m_{PG}) is projected to increase over time (Section 7 on Box A), the amount of plastic waste collected (m_{PCol}) is also expected to increase over time. However, the proportion of government budgets spent on waste management is likely to remain the same; in other words, GDP growth serves as a proxy for average government budget growth and a proxy for growth in spending on collection services. As a result, we estimated that the amount of plastic waste collected to be constrained not to exceed global GDP growth averaged at 3% per annum (92). From 2016 to 2040, $\%CR_P$ is then assumed to stay stable if projected m_{PCol} does not exceed annual GDP growth; if m_{PCol} does exceed annual GDP growth, (Eq. 8) is calculated as a proportion of the mass of plastic waste generated that is collected with m_{PCol} constrained by GDP growth at 3% (Table S26).

MFA:

To estimate MFA for $\%CR_P$, the annual growth constraint by GDP on m_{PCol} was removed. Instead, government spending is assumed to increase as needed to hit collection targets. We set the MFA targets in 2040 for $\%CR_P$ based on our expert panel consensus (Table S27). These MFA rates were used with the 2016 BL rate to extrapolate the CAGR from 2016 to 2040.

Uncollected waste (Arrow A2) and formal collection (Arrow B1) are plug values resulting from the residual flow out of Box A and Box B, respectively, after the flows from Arrows A1 and B2 are calculated as detailed above.

10.2 Collection for Recycling by the Informal Recycling Sector (Arrow B2/Box D/Arrow V1)

In our analysis, none of the interventions affected Arrow B2, Box D or Arrow V1; therefore, only the BL values were calculated.

We estimated the quantity of waste plastic collected for recycling by the informal recycling sector, hereafter ‘waste pickers,’ ($m_{P,CfR,WP}$; Arrow B2/Box D). This quantity depends on the number of the waste pickers (WP), the waste composition (percentage of plastic in waste collected by waste pickers) and their collection productivity (CPR) with regard to targeting and retrieving plastics. The WP and their productivity can be differentiated based on whether they operate in dumpsites (d) (unprotected landfills included) or on streets/ doorsteps (s) because of fundamentally different conditions in these two generalized settings.

We estimated WP per income category (Table S28). For LMI and UMI urban archetypes we calculated the WP in cities or countries as a proportion of the urban population (median number as reported by Linzner and Lange (93)) by the corresponding urban population (55). Whereas, it is acknowledged that waste pickers may operate in considerably lower numbers in rural areas because of the relatively low populations in the income categories where significant waste picker activity take place; therefore, we assumed the number to be zero for this analysis. Waste picker activities exist also in HI countries (94) but are comparatively insignificant and not well documented in comparison to the other parts of the world. However, because of the relatively larger populations living in urban areas, we assumed a proportion for WP in HI urban populations of 1 in 20,0000 based on expert panel consensus. Given that only 2 data points were found for LI (93), WP_{LI} was estimated to equal WP_{L}.

The proportion of waste pickers working at dumpsites ($\%WP_d$) was assumed to be 50% in areas of UMI, LMI and LI income categories where 100% of waste is mismanaged (69 countries (53)), according to the definition in Table S42 in Section 14. Therefore, we adjusted the 50% ratio using the proportion of mismanaged waste calculated in Table S43 in Section 14 as a weighting factor. WP_d are assumed to be zero in HI countries as landfills and dumpsites are generally restricted from public access.

We calculated the median worldwide daily CPR from raw data(95, 96) for waste pickers collecting (general) waste from dumpsites (CPR_d) at 50 $kg.d^{-1}$; and for those in the streets or from doorsteps (CPR_s) at 37 $kg.d^{-1}$ (93, 95–102). These values were adjusted by -25%, following expert panel consensus as their experience informed that part-time and elderly waste pickers, who have lower CPR, were likely missed in the data sources, as they are less likely to participate in surveys (adjusted $CPR_d = 38\ kg.d^{-1}$; adjusted $CPR_s = 28\ kg.d^{-1}$).

Daily plastic waste mass picked in dumpsites ($m_{P,CfR,WP,d}$) and in streets ($m_{P,CfR,WP,s}$) was calculated at 12 $kg.d^{-1}$ and 8 $kg.d^{-1}$ respectively, using the average (arithmetic mean) composition of plastic in MSW (30% wt. ar) (96–99, 103, 104). Annual plastic waste collection rates by waste pickers were calculated for each urban archetype using 21 working days per month (expert panel consensus) (Table S29).

The mass of waste collected per waste picker per urban archetype was estimated by dividing the respective estimated total annual mass of plastic waste collected by the estimated WP in the respective urban archetype (Table S30).

The estimated annual mass of plastic waste collected per waste picker (Table S29) was applied to the population (55) in each urban archetype and then allocated proportionally to each plastic category (rigid/flexible monomaterials; multimaterials) according to the arithmetic mean plastic waste composition as reported to be collected by waste pickers in streets (105, 106) and dumpsites (107–109) normalized to the same approximate basis/denominator (Table S31).

10.3 Collection for Recycling by the Formal Sector (Arrow C1)

'Collected for recycling' rate by the formal waste management sector ($\%CfR_{P,FO}$) was defined as the mass of MSW plastic waste collected with the intention of recycling ($m_{P,CfR}$) as a proportion of the mass of plastic waste collected ($m_{P,Col}$) (Eq. 9).

$$\%CfR_{P,FO} = \frac{m_{P,CfR}}{m_{P,Col}} \times 100 \qquad \text{Eq. (9)}$$

$\%CfR_{P,FO}$ was approximated as zero for LI, LMI, and UMI archetypes where the informal sector largely accounts for MSW plastic waste recycling (40).

BL:

For HI countries, we used the yearly mass of plastic waste generated and plastic mass recycled from 2010-2015 reported for Japan, the US and Europe as proxies to calculate HI plastic recycling rate ($\%R_P$). In all three cases $\%CfR_{P,FO}$ was not reported for MSW plastics, and where recycling rates were reported, the bases were mutually inconsistent. We corrected each dataset as follows.

Despite significant data available on plastic packaging recycling rates across Europe, recycling rates for MSW are not reported. One exception is a single data-point reported by Plastics Europe (29.7%) (110) in 2014. We used the growth rate in plastic packaging (PP) recycling rates reported between 2010 and 2015 (76) to backcast and forecast MSW plastic recycling rates for previous (Eq. 10) and subsequent (Eq. 11) years.

$$\%R_{PG,n+1} = \frac{\%R_{PG,n}}{\%R_{P:PP,n}} \%R_{P:PP,n+1} \qquad \text{Eq. (10)}$$

$$\%R_{PG,n-1} = \frac{\%R_{PG,n}}{\%R_{P:PP,n}} \%R_{P:PP,n-1} \qquad \text{Eq. (11)}$$

Where:

$\%R_{PG,n}$ is the MSW plastic (PG) recycling rate at year n;

$\%R_{P:PP,n}$ is the plastic packaging (P:PP) recycling rate at year n; and
n is the year.

To calculate the historical MSW plastic mass generated ($m_{P,G}$; wt. ar) in years 2010- 2015, we applied Eq. 12 to the MSW plastic waste generation rate (Mt y^{-1}) in 2016 reported by Material Economics (71).

$$\dot{m}_{P,G,n-1} = \frac{\dot{m}_{P,G,n}}{\%R_{P:PP,n}} \%R_{P:PP,n-1} \qquad \text{Eq. (12)}$$

Whereas the US and Europe report plastic recycling rates as the mass input to reprocessors (111, 112), in Japan the mass of MSW plastic recycled is reported as an output from the reprocessor (113), i.e. after an additional processing stage, which incurs losses. As a result, the mass reported to be recycled in Japan is understated in comparison to the US and Europe. To correct for this definition discrepancy, we adjusted the mass reported to be recycled in Japan by +27%, based on the average mass loss rate during reprocessing (Arrow I2/J1), reported by Hestin et al. (114).

With the recycled and generated mass adjusted to the same basis between 2010 and 2015 for the US, Japan and EU, the mass recycled was further adjusted by +20% to correct for losses during sorting (Arrow F3) (114). We then calculated the collected for recycling rate ($\%CfR_{P,FO}$) for 2010-2015 for Japan, US and Europe.

The CAGR for mass collected for recycling ($m_{P,CfR}$) and the CAGR for mass of plastic generated ($m_{P,G}$) for Japan, US and EU between 2010 and 2015 were used to estimate 2016 values for the mass of plastic waste collected for recycling ($m_{P,CfR}$) and the mass of plastic waste generated ($m_{P,G}$). The $\%CfR_{P,FO}$ for the HI archetypes is calculated as the weighted average among the US, Japan and Europe at 19.51%.

We used the calculated 2016 baseline rate for ‘collected for recycling’ for waste plastics ($\%CfR_{P,FO}$) and the historical rate of growth of plastic mass generated and plastic mass collected for recycling ($m_{P,CfR}$) for Japan, EU and the US to project the plastic mass generated and plastic mass collected for recycling for 2017-2040 (Table S32).

With the exception of Japan, the adjusted historical dataset (Table S32) showed an increase in both the plastic mass collected for recycling ($m_{P,CfR}$) and plastic waste mass generated ($m_{P,G}$) overall and individually for the US and EU. However, we assumed that this historical trend was driven by strong European regulation (e.g., (115, 116)), high oil prices and because it began from a comparatively low starting point. We also assumed that without intervention, a technical ceiling will be reached beyond which many plastics cannot be recycled.

For the baseline future projection to 2040, we assumed that the CAGR between 2010 and 2015 collected for recycling ($m_{P,CfR}$) and plastic waste mass generated ($m_{P,G}$) increased at half of the historical rate from 2016–2040, resulting in a net CAGR of 1.67% (Table S33) for plastic waste mass collected for recycling ($\%CfR_{P,FO}$; Arrow C1).

We assumed that the amount of waste generated ($m_{P,G}$; wt. ar) was the same as the amount of plastic waste collected ($m_{P,Col}$; wt. ar) for this analysis as Japan, US and EU have nearly 100% collection rates.

CCS:

NPEC's commitment to increase recycled content signals a demand for recycled feedstock, the effect of which was modeled as an increase in collection in order to fulfill this demand. The mass of demand was quantified by the Ellen MacArthur Foundation and estimated to be 5.4 Mt of recycled plastic by 2025 (86).

The companies that have committed are global and spread across archetypes. Our analysis assumes these companies will source a higher proportion from 'developed' countries as recycled content in plastic packaging requires high quality recycled plastics. We also assumed that it is realistic that most recycled content will be sourced by 2025 from developed countries where the collection and recycling infrastructure is already in place. Two/thirds of the demand is therefore modeled to be sourced from HI-U and one third from UMI-U.
Recycled content demand was assumed to be fulfilled only by rigid plastics and closed-loop mechanical recycling. In HI, the increased demand for recyclable feedstock is assumed to be met by a higher proportion of plastic segregated at source; Arrow C1 (Table S34). For UMI, the increased demand for recyclable feedstock is assumed to be met by a higher proportion of informal collection and sorting for closed-loop mechanical recycling; Arrow D1. The remaining model conditions were the same as those for the BL scenario, such that the increase in recycled content resulted in only an increase in arrows C1 and D1.

Companies were also assumed to continue to use similar shares of recycled content (as a percentage of total plastic) past 2025. While the share of recycled content was assumed to remain constant, if the total plastic mass increases, virgin plastic consumption could also increase proportionately.

MFA:

The expert panel discussed the existing and potential government action on recycling that could be implemented in HI, UMI and LMI countries between 2020 and 2040 and assessed feasibly achievable recycling rates. The expert panel consensus on 2040 % plastic collected for recycling rates ($\%CfR_{P,FO}$) in 2040 is shown in Table S35, broken down by rigid and flexible plastics. These rates were applied to 2016 baseline rates and extrapolated to estimate a growth rate for each archetype.

10.4 Mixed Collection by the Formal Sector (Arrow C2)

All collected plastic waste that is not collected for recycling by the formal sector (Arrow C2) was assumed to be collected mixed together with other waste materials (Box E) and sent for land disposal (Box N) or incineration with energy recovery (Box O). A portion of it will be mismanaged and potentially leaked into the wider environment (Box L) (Section 14 on Mismanaged Waste). We assumed the amount of waste recovered for recycling from mixed waste collection is negligible (Arrow E3). As Arrow C2 is a residual of the formally collected plastic (Box C) that was specifically collected for recycling (Arrow C1), Arrow C2 varies as a function of Box C and Arrow C1 and not by scenario conditions.

10.5 Sorting Losses from Formal Sector (Arrow F3)

The BL and the MFA values are shown below. There are no CCS values for Arrow F3.

BL:

We assumed a mass loss rate during formal sorting ($\%LR_{FO,SO}$) (Arrow F3) of 20% wt. ar for all plastic types for the whole period of 2016-2040, calculated based on the weighted average of plastic polymers reported by Hestin et al. (114) converted to our plastic categories (Eq. 13).

$$\%LR_{FO,SO} = (\%Y_{P:PP}\%PP)(\%Y_{P:OP}\%OP) \qquad \text{Eq. (13)}$$

Where:

$\%PP$ is the proportion of plastic packaging waste recycled in Europe (114)
$\%OP$ is the proportion of other plastic waste recycled in Europe (114)
$\%Y_{P:PP}$ is the plastic packaging pre-treatment (sorting) yield
$\%Y_{P:OP}$ is the ‘other plastic’ pre-treatment (sorting) yield

Data for all variables were from Hestin el al. (114). $\%LR_{FO,SO}$ is the same for all plastic categories and for the whole period of 2016-2040.

MFA:

For the MFA, we assumed formal sorting losses ($\%LR_{FO,SO}$) decrease from 20% in 2016 to 10% in 2040 based on an increase in the proportion of plastic that is technically recyclable due to a shift in the design of products to facilitate recycling, e.g., technological improvements, better sorting at source from consumer education, and better labeling for recycling.

10.6 Informal Sector Sorting Losses (Arrow D4)

For the informal sector, the mass lost during sorting (Arrow D4) was assumed to be less than the formal sector, as waste pickers do sorting by hand and generally ‘cherry pick’ the most valuable recyclable plastic waste at source. In contrast, sorting of formally collected waste is done either by machine or by MSW facility staff who are less likely to be specialized sorters and are less incentivized to achieve accurate separation. However, there are still losses as waste pickers inevitably increase the value of the waste plastic they sell to recyclers by removing caps and closures, labels and heavily soiled materials from the collected mass. As there were no published data on the level of losses, we assumed a loss rate of 5% wt. ar across all plastic categories and stable over time (as with the formal sector loss rate), based on the expert panel consensus. Since waste pickers are already assumed to be maximizing their sorting efficiency, we assumed that design for recycling intervention would have no impact over the BL values.

11. Recycling

We included both mechanical recycling and chemical conversion in our analysis of recycling stocks and flows. We defined mechanical recycling as closed loop (defined as recycling of plastic into any new application that will eventually be found in municipal solid waste, essentially replacing virgin feedstock in “Box A” of the system map) and open loop (defined as process by which polymers are kept intact, but the degraded quality and/or material properties of the recycled material is used in applications that might otherwise not be using plastic). Chemical conversion is defined as either Plastic to Plastic (P2P) – chemical recycling – or Plastic to Fuel (P2F), which is characterized as disposal in our system map and discussed in Section 12. Chemical conversion capacity in 2019 was still mainly in the development stage with only a few small scale commercial facilities in operation, though future capacities are planned (e.g.(117, 118)).

11.1 Open and Closed Loop Mechanical Recycling and Sorting Losses (Arrows D1, F1, I1, I2 and J1 and Box J)

BAU:

We assumed that all recycling between 2016 and 2020 was done via mechanical recycling and that no multimaterial/multilayer plastic waste flowed to mechanical recycling. The share of plastic waste flowing into closed loop and open loop mechanical recycling come from the formal (Arrows F1 and F2) and the informal sectors (Arrows D1 and D2).

For the HI archetypes, the percentage flowing to closed and open loop mechanical recycling and lost during sorting and the split among the plastic categories was based on an analysis by WRAP (119, 120) (Table S36a, Table S37a).

For the UMI, LMI and LI archetypes, all recycling comes from collection by the informal sector and will not change under BAU as it provides livelihoods to the waste picker population in these archetypes. As there are no reliable published data on the proportion of plastic waste collected by the informal sector flowing to open loop and closed loop mechanical recycling and losses during sorting, nor the allocation by plastic category, we relied on expert panel consensus for these percentages (Table S36b, Table S37b).

We quantified the mass recycled through closed loop (Arrow I1) and open loop (Box J) mechanical recycling, as well as the mass flowing to unsorted waste (Box L), based on estimated loss rates during these processes (Arrows I2 and J1). We assumed that the same loss rates applied to closed and open loop recycling, as well as to the plastic categories, and that these rates remained at 2016 levels through 2040 across all archetypes.

For the HI archetypes, the loss rate, estimated at 27%, was based on an analysis of data published by Deloitte and Plastics Recyclers Europe (119). For UMI, we assumed the same loss rate as HI. For LMI and LI, the loss rates were based on expert panel consensus at 20%.

MFA:

Both the increase in plastic going to closed loop recycling as well as the reduction in losses are based on what was considered technically and economically feasible by the consulted experts. This considers design for recycling, increased source separation and improvements in sorting and recycling technology.

MFA of recycling and sorting loss percentages in 2030 and 2040 were based on expert panel consensus. Percentages are expressed as a decrease in the proportion of plastic waste flow relative to 2016 BAU rates (Table S38).

In addition, we are assuming that the quantity of rigid (Table S36) and flexible monomaterials (Table S37) going to closed loop mechanical recycling increases by 2040. We are further assuming that – as under the BAU scenario – no multimaterial/multilayer plastic waste is flowing to mechanical recycling.

Please note, the flow of mass for flexibles in the SCS will partially go to chemical conversion. For HI, this mass will originate from mixed collection (Arrow E1) and is therefore not illustrated in Table S37.

11.2 Chemical Conversion – Reprocessing and Losses (Arrows D3, E1, K1, and K3) and Disposal Portion as P2F (Arrow K2)

P2P belongs to the "recycle" class of intervention, i.e., options aiming at maximizing environmental benefits and feeding into circular management of resources, while P2F refers more properly to "disposal," i.e. those options aimed at reducing post-collection leakage into the environment, similar to landfills and incinerators.

We modeled pyrolysis-based chemical conversion only in HI-U, UMI-U and LMI-U (no chemical conversion in rural and LI archetypes). We assumed that mass input to chemical conversion was sourced only from mixed plastic waste in HI-U (Box E, Arrow E1) and from informal collection (Box D and Arrow D3) in the UMI-U and LMI-U archetypes. We also assumed that the waste input came only from the flexible and multimaterial/multilayer plastic categories. This section describes the chemical conversion stocks and flows, which apply to both P2P and P2F, but as stated previously, P2F is considered as disposal.

BAU:

To estimate the total mass input for chemical conversion, we quantified the current total installed capacity. For HI, the chemical recycling capacity installed as of 2019 was estimated by summing the annual installed capacity of chemical recycling plants in HI countries. Most capacities currently listed under "chemical conversion" do not generate recycled feedstock and therefore is not considered recycling.

Three main sources were used to compile a list of facilities and the data. The reports consulted, in the order of publication dates, were 1) Closed Loop Partners Accelerating Circular Economy for Plastics, 2019 (118), 2) RICARDO Plastics to Fuel Market Report, 2017 (121) and 3) 4R

Sustainability Inc., Conversion Technology, 2011 (117). Where multiple reports had the same facility listed but different capacity figures, we used the most recently published figure. If a facility was listed but capacity figures were not provided in the report, we searched external sources in order of preference: facility websites, press releases, market reports and news articles. Some facilities were excluded in the estimate for the following reasons:

- They had a commission date of 2020 or later.
- They were in the lab stage of development.
- The end product was not a transportation/heating fuel or a fuel derivative
- They included a feedstock that was not exclusively plastic (e.g., all MSW or rubber)

The installed total annual capacity in 2019 from 28 facilities was estimated at 489 kt/year for HI. For LMI, the current capacity was estimated at 450kt/year based on 300 P2F facilities in India of 5t/d each. The capacity in UMI was estimated to be the same as in LMI based on expert panel consensus. We projected this capacity forward to 2040, assuming a slow historical CAGR of 2% under a BAU scenario. We assumed that there would be no development of chemical conversion for P2P, which represents the "recycling" application of chemical conversion technologies, because these technologies are currently practically nonexistent at commercial scale, and we did not assume any significant technological changes under BAU scenario. Based on these capacities, we assumed that the % of mixed waste collected going to chemical conversion (Arrow E1) in 2016 for both flexible monomaterial and multimaterial/multilayer was 1.4% for HI-U, 1.9% for UMI-U and 5.3% for LMI-U.

Under BAU, we assumed the reprocessing loss rate (Arrow K3) was the same as for mechanical recycling in HI archetypes (27%), resulting in a share of 73% of chemical conversion mass input going to P2F (Arrow K2). We assumed that under BAU all chemical conversion is for P2F, and as a result, these rates remain the same through to 2040. Given the nascency of this technology with very low mass throughput, we are applying an uncertainty range of +/- 20% to the mass figures.

MFA:

For MFA, we assumed there would be an increase of chemical conversion capacity, and that it would convert both P2P - recycling and P2F - disposal.

We based the maximally foreseen growth rate for chemical conversion (Box K) on the CAGR of ethanol production in Brazil between 1975-95, a period in which the Brazilian government aggressively pushed the development of ethanol production and incentivized it accordingly. Based on expert panel consensus, the historical ethanol production trajectory in Brazil was assessed to be a good proxy for the potential trajectory of chemical conversion due to the similarly capital-intensive nature as well as interest by governments and the industry. The CAGR was calculated to be 16.5%.

This CAGR was then used to project the mass of chemical conversion feedstock to 2040 for both flexible monomaterial and multimaterial/multilayer. In addition to this growth constraint, we constrained the mass for each of these two plastic types to a maximum 50% of all collected flexible monomaterial and multimaterial/multilayer plastic waste in any given year (Box C). The mass flowing to chemical conversion is calculated as the smaller of these two constraints.

For feedstock sourced from informal collection for chemical recycling, we assumed a maximum of 10% of informal collection by 2040.

For the actual share of chemical conversion and the split between P2F and P2P, we assume a gradual shift from only P2F facilities to P2P facilities in all archetypes starting in 2030. This results in both reaching parity in 2040: 45% P2F, 45% P2P, and 10% losses (Table S39).

12. Disposal

We distinguish between two types of disposal technologies: engineered landfill and incineration with energy recovery. We also classified chemical conversion for P2F in the disposal category as discussed in Section 11. Dumpsites or unmanaged landfills are not included as they are considered mismanaged waste. Incineration without energy recovery has been excluded after careful deliberation with the expert panel as these make up an insignificant share of plastic waste treated at the global level (only a few legacy plants are still in use today).

12.1 Incineration with Energy Recovery (Arrow M1 and Box O) and Engineered Landfill (Arrow M2 and Box N)

BAU:

The proportion of managed waste (Arrow L1 and Box M) that was disposed either in an engineered landfill (Arrow M2, Box N) or incineration with energy recovery (Arrow M1, Box O) was determined based on analysis using published reports and expert input (Table S40). These trends were projected to remain the same throughout 2016 to 2040 in the UMI, LMI and LI archetypes, yet overall mass may decrease as we reduce overall managed waste mass through application of other levers in the model.

We used the national disposal statistics from World Bank's WAW 2.0 dataset (30) to estimate the proportion of waste disposed to engineered landfills and incineration with energy recovery (53). Historic trends were used to estimate changes in these proportions over time. Most notable was EU countries where incineration with energy recovery is growing. The CAGR of material being disposed of in engineered landfill in HI countries was calculated by taking the average CAGR of engineered landfill in the EU by mass from 2006-2016 (110). This EU figure was adjusted for HI by assuming US stays flat and multiplying CAGR by EU proportion of mass for HI. (Table S40).

The rationale and assumptions were that in LMI and LI archetypes, all managed waste is assumed to be disposed of in engineered landfills rather than incineration with energy recovery as landfilling is a more affordable option.

12.2 Chemical Conversion, P2F (Arrow K2)

P2F estimates are discussed in Section 11.2 under chemical conversion.

13. International Import and Export of Plastic Waste

International trade in plastic scrap ($m_{P,INT}$) (Arrow F4/Box G and Arrow H1/Box H) is undergoing considerable change at the time of this analysis due to the Chinese import ban on waste plastics in January 2018 and subsequent changes to import policy in several other common worldwide destinations. Therefore, we based our analysis on trade that took place after the Chinese 'ban' disruption in 2018. We assumed the mass of plastic scrap ($m_{P,INT}$) traded in 2018 is equal to the mass traded in 2016 in our analysis.

Monthly traded mass data were obtained from the UN Comtrade database (122) for commodity code HS3915 (waste, parings and scrap, of plastics) for all countries in 2018. Data were downloaded between 20 and 23 March 2019 with an updated download on 19 August 2019 for select countries.

Exported monthly mass data for 38 countries and imported monthly mass data for 36 countries were estimated based on the mean average of the most recently reported months in 2018 or the whole of 2017. No corrections were made for seasonal or year-to-year changes in trading in these adjusted cases due to the unpredictability of the market (data accessed 20 and 23 March 2019).

For China, Malaysia, Thailand, Vietnam and Indonesia, the data were initially extrapolated as explained in the paragraph above. However, as a result of significant change in import policy reported for these countries (123–127) over 2018, we decided to download more up-to-date mass data from UN Comtrade reported by exporters to these countries (data accessed 19 August 2019).

Imported plastics scrap mass data ($m_{P,IMP}$) (Arrow F4/Box G) and exported plastic scrap mass data ($m_{P,EXP}$) (Arrow H1/Box H) reported should in principle balance on a global scale; however, historical analysis shows that this is seldom the case (128) due to reporting inconsistencies. Because our model requires a mass balance, the reported import data ($m_{P,IMP}$) were normalized to the reported export mass data ($m_{P,EXP}$) (Eq. 14, Table S41).

$$adjm_{P,IMP,i} = \sum m_{P,EXP} \frac{m_{p,IMP,i}}{\sum m_{P,IMP}} \qquad \text{Eq. (14)}$$

Where:

$adjm_{P,IMP,i}$ is the adjusted mass of plastic for the i country category;

$\Sigma m_{P,EXP}$ is the total mass of plastic reported to be exported for all income group categories; and

$\Sigma m_{P,IMP}$ is the total mass of plastic reported to be imported for all income group categories.

In the absence of any generalizable evidence on the rurality of plastic scrap traders, we assumed that all imports and exports take place between urban archetypes. Because in our model the inter-archetype mass traded is comparatively small, it is not likely to result in any considerable impact on model output.

As the Harmonized system (129) does not differentiate between rigid monomaterials, flexible monomaterials and multimaterials, we assumed that only rigid monomaterials were traded internationally as they have the highest value, acknowledging that in reality some flexible monomaterials are likely to be traded internationally.

BL:

Growth in global trade was assumed to be at the same rate as the growth in plastic waste generation in HI archetypes (Section 5).

MFA:

Through expert panel consensus, we set an inter-archetype export (e.g., between high-income archetypes and low-income archetypes) target reduction of 80% by 2030 and 90% by 2040, relative to BAU. Intra-archetype import and export mass remains the same by mass relative to BAU throughout the analysis time period to allow for some regional trading within neighboring countries, especially in LI, LMI and UMI countries, which might develop regional hubs to increase efficiency by aggregating plastic for recycling. We assumed the mass is the same relative to BAU but not constant over time. BAU import/export mass grows at the same rate as plastic in HI countries as we explain half a page above under “BL.”

14. Mismanaged Waste

14.1 Post-collection Mismanaged Plastic Waste (Box R and Arrow L2)

We defined mismanaged plastic waste ($m_{P,MISMAN}$; Box R and Arrow L2) as collected plastic waste that has been released or deposited in a place from where it can move into the natural environment (intentionally or otherwise). This includes dumpsites and landfills that are not managed by applying daily cover (130) to prevent waste from interacting with the air and surface water.

We assumed the rate of mismanaged plastic waste ($\%_{P,MISMAN}$) to be identical to the rate of mismanaged MSW, as a whole, ($\%_{MSW,MISMAN}$) reported in the Kaza et al. 2018 dataset (30), using the classifications in Table S42 weighted for each income category by the mass of MSW waste generated in each country.

We assumed that the amount of mismanaged waste in urban and rural areas is proportional to the amount of uncollected waste in urban and rural areas (Section 10) applying Eq. 15 and Eq. 16 to calculate the proportion of managed waste in each archetype.

$$\frac{\%u_{MSW,MAN}}{2} = \left(\frac{\%W_{MSW,MAN}}{\%u_{MSW,COL}}\right) * \left(\%u_{MSW,COL} + \%r_{MSW,COL}\right) \qquad \textbf{Eq. (15)}$$

$$\frac{\%r_{MSW,MAN}}{2} = \left(\frac{\%W_{MSW,MAN}}{\%r_{MSW,COL}}\right) * \left(\%u_{MSW,COL} + \%r_{MSW,COL}\right) \qquad \textbf{Eq. (16)}$$

Where:

$\%u_{MSW,COL}$ is the proportion of urban MSW collected as a % of total waste generated ($m_{MSW,G}$);
$\%r_{MSW,COL}$ is the proportion of rural MSW collected as a % of total waste generated ($m_{MSW,G}$);
$\%u_{MSW,MAN}$ is the proportion of urban managed MSW as a % of disposal;
$\%r_{MSW,MAN}$ is the proportion of rural managed MSW as a % of disposal; and
$\%W_{MSW,MAN}$ is total managed waste as a % of disposal.

BL:

The resulting proportions of managed waste (Arrow L1) in each archetype are shown in Table S43.

We assumed that the mass of managed plastic waste ($m_{P,MAN}$; Arrow L1 and Box M) as a proportion of 'unsorted plastic waste' (Box L) does not change until 2040. However, in the cases where the mass of managed plastic waste ($m_{P,MAN}$) grows faster than predicted growth in GDP, we constrained the mass of managed plastic waste ($m_{P,MAN}$) not to grow faster than the rate of GDP growth. The latter was assumed as a proxy for government spending, and thus, spending on managed disposal facilities. In practice, this is only relevant for UMI-U, which shows a reduction in managed plastic waste ($m_{P,MAN}$) by 2040 relative to 2016.

MFA:

SCS projected proportions of managed plastic waste ($m_{P,MAN}$) shown in Table S44 were chosen following expert panel consensus on the realistically achievable upscale in basic waste treatment and disposal infrastructure across all archetypes between 2020 and 2040.

14.2 Open Burning

BL:

We based the rate of collected plastic waste that is open burned in dumpsites ($\%OB_{P,DS}$) and the rate of uncollected plastic waste open burned residentially ($\%OB_{P,RES}$) on the rates of uncollected MSW open burned in dumpsites and the rate of uncollected MSW open burned residentially reported by Wiedinmyer et al. (43) (Table S45).

14.3 Transfer of Plastic Waste from Land into Waterbodies

Sources and pathways

There are multiple, complex sources and pathways that result in plastic waste entering natural water bodies ($m_{P,AQLEAK}$), such as through land drains, sewerage, erosion of coastal landfills, as well as across the surface of the land by wind or water (131, 132). Plastic waste is also directly dumped into waterbodies by residents pre-collection and by waste management operators post-collection (133). However, there is limited empirical data to evidence the quantities of plastic waste that transfer through each of these pathways and into the aquatic environment; the current research (128, 134, 135) applies objective reasoning to make estimates based on the quantities of ‘mismanaged waste’ being generated in relation to proximity to rivers or coastal waters.

Here we used expert panel consensus to estimate and identify sources of plastic waste that are at risk of entering the aquatic environment and the generalized pathways through which they are likely to flow through to reach rivers and coastal waters (Table S46).

14.4 Transfer Ratios

BL:

Direct dumping by residents

Uncollected plastic waste ($m_{P,UNCOL}$) dumped directly into waterways and coastal waters by residents ($m_{P,DDRES}$) was approximated from the results of a pan archipelagic survey (136) of the waste management habits of Indonesian people. A weighted average of survey responses indicated that approximately 8% of waste may be deposited directly into waterbodies by household in Indonesia. For our model, we conservatively estimated 10% within 1 km of rivers and coastal waters and 0.1% beyond, without differentiating between plastic types.

Direct dumping by collection vehicles

There is limited evidence to indicate the proportion of post-collection mismanaged plastic waste ($m_{P,MISMAN}$) that is deliberately dumped into waterbodies by collection vehicles ($m_{P,DDCOL}$); therefore, expert panel consensus estimated this at 5% regardless of proximity to water bodies.

Transfer from terrestrial dumping and dumpsites

In the absence of empirical research that quantifies the proportion of plastic waste that physically moves from terrestrial dumpsites into the terrestrial environment ($m_{P,DS,TRAN,TL}$; Arrow V4) and aquatic environment ($m_{P,DS,TRAN,AL}$; Arrow V3) and from terrestrial dumping to aquatic environment ($m_{P,DTDUMP,TRAN}$; Arrow T1), we relied on expert panel consensus to identify the following principles that were used to estimate the ratios between waste transfer from diffuse terrestrial dumping and dumpsites.

1. Plastic debris flows downhill, mobilized by wind and water and drawn by gravity to lower ground.
2. Mismanaged plastic waste ($m_{P,MISMAN}$) that has been collected and deposited in dumpsites or uncovered landfills becomes buried relatively quickly, and is therefore less likely to be affected by wind, rain or surface water.
3. Uncollected plastic waste ($m_{P,UNCOL}$) deposited on land is dumped less discriminately than waste deposited in dumpsites or uncovered landfills and is therefore more spread out across the terrestrial surface. Some will become buried in areas where waste has built up, but we consider the probability of transmission into waterways to be considerably higher than in dumpsites or uncovered landfills.
4. Lighter plastics such as films/foils are more likely to transfer from land into the aquatic environment, being more susceptible to the forces of wind and surface water.
5. For each plastic category, the rate at which post collection mismanaged plastic waste leaks out of dumpsites is the same regardless of distance from waterbodies. When a dumpsite/unsanitary landfill is < 1 km from a waterbody, it is assumed that 50% of the material which escapes remains on land (terrestrial pollution, $m_{P,DS,TRAN,TL}$) and 50% enters a waterbody (aquatic pollution, $m_{P,DS,TRAN,AL}$). When a dumpsite/unsanitary landfill is > 1 km from a waterbody, a higher proportion of post collection mismanaged plastic waste leakage will remain on land (terrestrial pollution, $m_{P,DS,TRAN,TL}$), and only a small proportion will enter a waterbody (aquatic pollution, $m_{P,DS,TRAN,AL}$).

Values in Table S47 were used to differentiate the physical movement of plastic types after being deposited in dumpsites and uncovered landfills.

The quantities of material at risk of leaking (uncollected waste (Box Q), and post-collection mismanaged waste (Box R)) will vary between income groups, and this will impact the final quantities of material leaking into water. However, we assumed that the economy of a particular country and rurality of its residents does not impact the physical behavior of waste plastics because the plastics travel from land into the aquatic environment, and therefore the ratios that describe transfer of waste from diffuse terrestrial dumping and dumpsites (Arrows T1 and V3; Table S47) do not vary by archetype.

MFA:

Based on expert panel consensus, it is assumed that deliberate dumping by waste collection vehicles into water (Arrow R1) could be reduced from 5% to 1%.

14.5 Dumpsite Recovery (Arrow V1)

BL:

In countries with open dumpsites or unsanitary landfills where public access is not restricted, members of the informal recycling sector are thought to recover significant quantities of material for recycling. This collection is represented by Arrow V1 (Figure S1), discussed in more detail in Section 10.

14.6 Post-Pollution Collection from Aquatic Environments (Arrow W1)

BL:

Currently there are two major types of efforts to recover plastics from aquatic environments: manual removal (i.e., recovery of plastics from aquatic environments directly by volunteers or others, such as beach clean-ups) and removal by technology (i.e., recovery of plastics from aquatic environment with equipment/technology, such as river traps and open ocean recovery with vessels).

We reviewed publicly available information and consulted with several groups developing technologies and equipment to remove/collect plastic from the aquatic environment and concluded that the plastic that these technologies could collect were negligible at the global scale for several reasons: (1) the current plastic mass collected through these efforts is negligible (estimated at no more than 0.05% of annual plastic flows to the aquatic environment); (2) there are no reliable projections for how these technologies can scale over time; and (3) the collection costs of these methods are not currently publicly available and were not disclosed by any of the groups we consulted with, so the expert panel could not confidently provide an expert opinion on their impact on plastic flows.

As a result, we parameterized post-pollution collection using data from the International Coastal Cleanup, a global beach clean-up program started in 1986 that has a database with a standardized reporting method and a long time-series (137).

15. Microplastics

Microplastics are defined in this study as pieces of plastic between 1 µm and 5 mm in size that enter the environment as such – widely called primary microplastic (138). We do not include the breakdown of mismanaged macroplastic waste in our analysis of microplastics as that has been accounted for as macroplastic, and there is currently insufficient understanding of how macroplastics degrade to microplastics to model this process. Neither do we quantify nanoplastics, defined as particles < 1 µm in size, due to data limitations. Importantly, both primary and secondary microplastics and nanoplastics may be considerable sources of pollution causing harm to living organisms (139).

Out of the approximately 20 potential primary microplastic sources, we modeled four main sources representing an estimated 75-85% of microplastic pollution: tire abrasion (TWP), pellet loss, textile microfibers and microplastic ingredients in PCP, including the full microsized spectrum of ingredients (61, 140). We selected these four sources based on the availability of existing research, information on relative pollution masses and the ease/understanding of potential solutions for each source (141).

System maps were developed for each source (Fig. S3, S4, S5, S6); BAU values were identified or calculated and major intervention points and assumptions under the MFA/SCS were identified (Table S57). Additional information on each source and details on the assumptions and calculations underlying the values used in the analysis are explained below and presented in the accompanying Excel file (https://dx.doi.org/10.5281/zenodo.3929470).

A note on terminology: the sections on the four microplastic sources below use two different terms to refer to sewage collection and treatment based on current scientific understanding of their environmental distribution and fate. Tire microplastics and plastic pellets were modeled as entering combined sewage systems, which include both stormwater overflows and sewage collection and treatment, because data are not available on microplastic concentrations in stormwater or the effectiveness of different sewage treatment types in removing these two types of microplastics. The usage of this term is nonetheless consistent with previously published studies. In contrast, more is known about the behavior of textile microfibers and personal care products in sewage treatment, and thus this component could be modeled separately for these two sources, including removal by different levels of sewage treatment.

15.1 Microplastic Source: Tires

The accumulation of TWP in the environment generated by the abrasion of tires has been recognized since the 1960s (142), but the occurrence of these particles as a major proportion of microplastic pollution is a relatively recent concept (143–146), with desk-based estimates indicating that TWP could account for around half of all microplastic emissions.

System map for TWP

TWP are generated when frictional energy at the tire-road interface creates shear forces and heat leading to the generation of microparticles (147); these losses occur from tire wear on roads and on runways in the system map to soil, air and local waterways (Figure S3). Losses during tire manufacturing and recycling were not modeled due to limited data.

TWP can be carried by wind; 1-10% of TWP may become airborne (148) with the remaining coarser particles deposited close to the point of emission (149, 150). There is limited empirical data on the transmission of TWP by wind, but they can be detected settling from the atmosphere at distances of 50 m from roadways (expert panel consensus). TWP in stormwater can pass directly to waterbodies (streams, rivers, ocean) and become aquatic pollution, or be captured in combined sewage systems or sustainable drainage systems (SuDS). Once TWP are removed (Box MA in Figure S3), they may re-enter the environment as terrestrial pollution via the land application of sewage sludge, or they may be disposed of in dumpsites or sanitary landfills; in both cases, TWP are considered unmanaged waste. TWP may also be disposed of as managed waste via thermal treatment with energy recovery or in a sanitary landfill.

Detailed explanations of the assumptions, values, growth projections and sources used to calculate the masses and flows through each of the microplastic systems are presented in the accompanying Excel file (https://dx.doi.org/10.5281/zenodo.3929470). The following sections broadly describe the assumptions and calculations for each of the modeled sources.

Calculations and assumptions underlying the system map and model for TWP

Road losses under BAU (Box MTA)

Road losses of TWP were calculated using data on km driven per capita for four vehicle types – passenger cars, light vans (<3500 kg), motorbikes and trucks/buses – for each of the archetypes (Eq. 17). Data from the EU and USA were assumed to represent the HI archetype, data from China and Mexico were assumed to represent the UMI archetype, data from India were assumed to represent the LMI archetype and values for the LI archetype were calculated by extrapolating rates of motor vehicle ownership in LI countries.

$$L_{TWP\text{-}R} = D_{VT} * LR_{TWP} \qquad \text{Eq. (17)}$$

Where:

$L_{TWP\text{-}R}$ is the mass of TWP lost on roads in metric ton;
D_{VT} is the distance driven in km for each vehicle type per archetype (weighted by urban or rural population); and
LR_{TWP} is the TWP loss rate in mg/km for each vehicle type based on published sources (assumed to be the same for both urban and rural).

Data from the USA (151) on the proportion of km driven on urban motorways/roads and rural motorways/roads were assumed to represent global traffic activity, and L_{TWP} was allocated to urban/rural as shown in Table S48.

No distinction was made between paved and unpaved roads; it was assumed that TWP losses are the same on both road types.

Runway losses under BAU (Box MTB)

Losses of TWP on runways in metric ton (L_{TWP-RY}) were calculated as shown in Eq. 18:

$$L_{TWP-RY} = F_A * LR_F \qquad \text{Eq. (18)}$$

Where:

F_A is the annual number of flights for each archetype as reported by the World Bank (152); and

LR_F is the loss rate per flight for takeoff and landing (278 g) (153).

Transmission Factors: Soil, Air and Waterways

Transmission factors for TWP to soil, air, waterways and combined sewage treatment were determined using data from two studies in Europe, which were assumed to represent the HI archetype (61, 154) (Table S49). The proportion of TWP runoff to waterways was calculated as a remainder of the other transmission factors for air, soil and capture by combined sewage treatment/SuDS. The proportion of TWP captured in combined sewage treatment for the other archetypes was weighted by the percentage of the population connected to sewage treatment in the archetype.

Transmission factors: capture and disposal

Capture of TWP in SuDS was assumed to occur only in the HI archetype. TWP were considered as managed in HI-U (61, 154) (e.g., via the use of various types of filter systems), while TWP in HI-R were considered mismanaged/terrestrial pollution (Table S50). The proportion of TWP going to managed disposal (thermal treatment with energy recovery or engineered landfills) or to dumpsites/unsanitary landfills was determined based on the flows in the macroplastic model (Table S51). Disposal of TWP as terrestrial dumping includes land application of sewage sludge. It was assumed that TWP disposed into the terrestrial environment (e.g., to soil) remain trapped and do not reach aquatic systems.

15.2 Microplastic Source: Pellets

Several global studies have identified the loss of plastic pellets (micro-sized granules usually shaped like a cylinder or disk) as an important source of microplastic pollution (6, 61). Pellet loss may occur across the plastic supply chain at a wide range of facilities, including production, conversion, recycling and logistics facilities. Losses of plastic pellets (micro-sized (≤ 5mm) granules usually with a shaped like a of cylinder or a disk) occurring across the plastic supply chain at a wide range of facilities, including production, conversion, recycling and logistics facilities, have been considered a significant source of microplastic pollution to the ocean by several global studies (6, 61).

System map for pellets

Plastic pellet losses occur in three places in the system map (Figure S4): 1) during handling by producers, intermediary facilities and processors; 2) during transport at sea; and 3) during recycling processing. Losses at intermediary facilities include loading and unloading of pellets (61). Losses during road transport were not modeled as most losses occur during handling within facilities (61). Pellet losses during sea transportation were modeled as direct ocean pollution. Pellet losses during handling and recycling were assumed to directly enter drains, from which they either end up captured in wastewater treatment facilities (in the case of locations with combined sewage systems) or captured in SuDS (considered as mismanaged environmental pollution), with the remainder entering oceans and rivers. Only pellets that are captured for disposal, including those removed during sewage treatment and disposed of via landfill or incineration with energy recovery, were considered managed waste. Pellet losses to aquatic and terrestrial systems and into dumpsites, including land application of sewage sludge, were considered mismanaged waste.

Calculations and assumptions underlying the system map and model for pellets

Plastic/pellet production under BAU

The mass of plastic production under BAU was calculated using archetype-specific MSW plastic demand from the macroplastic model, scaled up to include all plastic by using a correction factor from PlasticsEurope for 2016 (110) (Table S52). Other assumptions were as follows:

- The mass of pellets handled by processors was assumed to be the same as the mass produced, as all produced plastic passes through a processing phase.
- The mass handled by intermediary facilities was calculated as the mass of plastic produced, and it was assumed that pellets are handled 2.5 times between the production and the use phases (61).
- Recycling mass from 2016 to 2040 for BAU and the SCS was taken from the macroplastic model's recycling rate for plastic MSW.

Pellet transport and losses under BAU

The mass of pellets transported by sea under BAU was calculated using archetype-specific MSW plastic demand from the macroplastic model corrected by global export data from the UN COMTRADE database (122), and share of goods transported by sea in the EU - 47.6% (155) - with the same value assumed for all archetypes. The pellet loss rates were assumed to be the same for all archetypes (Table S52).

Pellet capture and disposal

All pellets lost during production, recycling and handling were assumed to enter drains from where they are directed to combined sewage treatment, SuDS or waterways and the transmission factors were determined using data from European study (61) (Table S53). It was assumed that pellets disposed into the terrestrial environment (e.g., to soil) remain trapped and do not reach aquatic systems. Assumptions for pellet treatment and disposal after capture are the same as for TWP (see Table S47, S48).

15.3 Microplastic Source: Synthetic Textiles

Several global studies have found plastic microfiber pollution resulting from production and use of synthetic textiles to be a key source of microplastic pollution in aquatic systems (6, 61, 131). The system map and model for this source focused on aquatic release pathways, as the data for the air pathway are very limited (Figure S5).

System map for textiles

Textile microplastic losses occur in three places in the model: 1) pre-wash and processing during production; 2) hand washing during the use phase; and 3) machine-washing during the use phase. Airborne, dry cleaning losses and losses from textile recycling processes (shown as grey boxes) were not modeled, as there are insufficient data about these losses. However, they are likely to also contribute significantly to environmental pollution (156). Each of these losses has different pathways to sewage treatment, waterways or soils. Sewage treatment levels (primary, secondary and tertiary) have different efficiencies of microplastic removal (157) and vary across archetype in their availability; secondary and tertiary treatment are most common in the HI archetype while primary treatment predominates in LMI and LI (see below for details on how treatment was modeled). Stormwater overflows during periods of heavy rain may cause direct release to waterways. Microfibers ending up as aquatic pollution, and those that go to terrestrial pollution/dumpsites, including land application of sewage sludge, were considered "mismanaged" microfibers, while the fate of "managed" microfibers was either disposal to thermal treatment with energy recovery or to engineered landfills.

Calculations and assumptions underlying the system map and model for textiles

Textile production, use and losses under BAU

Global textile production in 2017 was approximately 105 Mt, with a projected CAGR of 3.2% (158). Microplastic pollution from textile production was calculated as follows (Box MSA):

$$L_{Tex} = P * M_A * C_A * W_P * L_{PW} \qquad \text{(Eq. 19)}$$

Where:

P is global textile production;

M_A is textile market share per archetype;

C_A is the share of synthetic clothing on the market in a given archetype (weighted by population for urban vs. rural);

W_P is the number of production washes textiles are subject to (assumed to be 4); and

L_{PW} is the average loss rate per kg of textile washed based on few data points for polyester, nylon and fleece of different age (assumed to be the same as for textiles in the use phase; see Table S59 below).

The archetype share of global textile production (M_A) was based on world trade data and was assumed to be 36.8% for HI, 46.7% for UMI, 16.5% for LMI and 0% for LI (159). The share of synthetic clothing on the market (C_A) was 48% for HI based on data for developed countries and 68% based on data for developing countries allocated evenly across UMI, LMI and LI (6).

Production microplastic losses were modeled for all textiles, not only clothing. Household washing was only modeled for synthetic clothing, i.e. washing of bed linens was not modeled on the assumption they are primarily made of cotton and are an insignificant source of synthetic fibers compared to clothing. Differences in washing temperature among countries were assumed to have a negligible overall impact on loss rates.

Household washing machine ownership was used as a proxy for the share of clothes washed by machine. Handwashing of clothing was assumed to be negligible and commercial washing was assumed to account for the remainder of household machine washing in the HI archetype and in UMI-U. Commercial washing was assumed to be negligible in other archetypes while hand washing was calculated as the remainder of the data point for machine-washing in UMI-R and both urban and rural LMI and LI. Losses via air, during wear or from dry cleaning, were not modeled due to insufficient data, but these are likely significant sources of environmental pollution.

Textile losses from the use phase (Boxes MSB and MSC) were therefore modeled as the product of the values given in Table S54 for each archetype (assumed to be the same for both urban and rural), multiplied by the market share of synthetic clothing stated above (48%/68%). Details on sources and assumptions underlying these values can be found in the accompanying Excel files.

Textile microplastics capture and disposal under BAU

The primary mechanisms of capture for textile microplastics under BAU were stormwater management and sewage treatment. We assumed that 100% of uncollected wastewater goes directly to waterways **(**Arrows MSA1, MSB1 and MSC1), and that direct losses to soil were 0% for both HI and UMI, and 62% and 25% for LMI and LI, respectively (Arrow MSB3). Textile microplastic pollution resulting from stormwater overflow was assumed to be 4% for all archetypes based on data for the HI archetype (61) (Box ME, Arrow MD1).

Connection of washing machines to sewage collection was based on UN data (160); if sewage collection existed for an archetype, handwashing and production washing were assumed to likewise be connected to collection. Sewage treatment level was determined based on data for Europe for the HI archetype (161); as an average of data for six countries for the UMI archetype (162–164); as an average of data for 14 countries for the LMI archetype and was assumed to be 100% primary treatment for the LI archetype due to lack of data (162) (see the accompanying Excel file for full details). Additional assumptions regarding sewage treatment can be found in (Table S55). Values for urban and rural archetypes were assumed to be the same.

Sewage treatment in textile production facilities was assumed to be at the primary level and aligned with national estimates of the share of sewage treated as there is lack of data on the actual share. The textile industry may use all three types of treatment but would rather avoid producing sludge due to high cost of sludge disposal (165), and there are currently no requirements for microfiber removal from sewage.

Microplastics disposed into the terrestrial environment (land, soils, etc.) were assumed to remain trapped and not reach the aquatic environment (this is a simplifying assumption, as recent studies have demonstrated that airborne microfibers reach remote locations (166)).

15.4 Microplastic Source: Personal Care Products

Microplastics are added to PCP for many purposes; though public and policy attention has focused on plastic microbeads added as abrasives to products such as body scrubs and toothpastes, personal care products may contain other types of microplastic as ingredients (61, 167).

System map for PCP

The system map for PCP (Figure S6) includes both “stay-on” and “wash-off” products as sources for microplastic pollution. Losses occur only via consumer use, as the data on manufacturing losses are insufficient to model. Microplastics in “wash-off” products may enter waterways directly or via sewage treatment systems, while those in “stay-on” products may follow both pathways as well as a disposal pathway that applies when products are removed using absorbent materials (e.g., cotton pads or tissues) that are disposed of as MSW. PCP microplastic pollution of aquatic systems may occur via stormwater overflows, ineffective sewage treatment or direct release to waterways. Microplastics captured in sewage treatment may enter the terrestrial environment via land application of sewage sludge or the unmanaged disposal of sludge to dumpsites/unsanitary landfills. PCP microplastics as solid waste are either captured and disposed of in engineered landfills or dumpsites/unsanitary landfills.

Calculations and assumptions underlying the system map and model for PCP

Global PCP production and market share under BAU (Boxes MPA, MPB, MPC, MPD)

Total global PCP production in 2016 was 11,446,016 t, with a projected CAGR of 1.44% (168). The archetype market share of PCP use was calculated from the HI-U share (32%) (131). Market share for the other archetypes was weighted by population of the given archetype (e.g., HI-R: 8%; UMI-U/R:16/9%; LMI-U/R:11/18%; LMI-U/R LI: 2/4%). Data for Europe on the share of the PCP market that is “stay on” vs. “wash off” and the microplastics concentrations in PCP was assumed to apply to all archetypes (Table S56) (61).

PCP losses, capture and disposal under BAU

PCP losses via sewage treatment (Box MD) and stormwater overflow (Box ME) were the same as those modeled for textiles (Table S56). Microplastic losses to solid waste disposal (Box MPF; Arrow MPD3) were based on data for Europe indicating that 71% of consumers remove makeup with cotton pads and dispose of them as solid waste; values for the other archetypes were assumed to be 10% less (60% for UMI, 50% for LMI and 40% for LI). The percent share of sewage treatment type (Boxes MF, MG, MH) and the capture rates for each sewage treatment type (Box MA) were the same as those used for textiles (Table S55). Assumptions for PCP treatment and disposal after capture are the same as for TWP (Table S50, Table S51).

15.5 Intervention Levers and Assumptions for the Four Sources Modeled

The twelve intervention levers modeled for each of the four sources are described in Table S57 below. The interventions included in the “Reduce” and “Substitute” categories were modeled in the RSS; all interventions listed were modeled in the SCS.

16. Costs and Revenues

We modeled the waste management costs associated with each of the scenarios with two main cost considerations: projected annual capital expenditures (capex) and operational expenditures (opex). Capital expenditures are associated with major purchases or upgrades, such as industrial plants, equipment, vehicles or land. Operational expenditures are ongoing costs, including producing and converting new material, running recycling plants, wages and administrative expenses.

Costs were calculated subsequent to the mass flow calculations in the model to provide a rough order-of-magnitude comparison of waste management system costs among scenarios. We assumed that the costs of each activity did not affect the mass flows in the system map, i.e. the model was not sensitive to cost elasticity. For each activity (e.g., collection, recycling, disposal, etc.), we collected data on opex and capex for each geographic archetype. We subsequently made assumptions on the impact that the scale of a technology will have on its cost, as described in detail in the "Growth Rates and Learning Curve" section below (16.1).

Opex were calculated on a per metric ton basis for each component of the system map and then applied to the mass of material that "flows" through the relevant activity in any given scenario.

Capex were calculated for each scenario by comparing the previous year's infrastructure capacity (production plants, waste disposal facilities etc.) with the capacity needed in the current year, assuming that any shortfall in capacity would to be filled by building new infrastructure. We applied a turnover rate, assuming that 2% of existing capacity reaches the end of its functional life each year and needs to be replaced by new infrastructure capacity. The exceptions to this were for formal collection, where we assumed a 5% turnover rate to reflect the fact that much of the relevant investments would be in vehicles rather than buildings; and landfill, where we assumed zero turnover. For each type of capacity, the quantity needed in each year was multiplied by the investment cost needed per metric ton of capacity.

Similarly, we collected revenue data for revenue-generating activities per archetype: recycling and incineration with energy recovery. While the prices for virgin plastic and recyclates are closely correlated with the price of oil, we assumed oil prices remain flat over time. We assumed that the sales price of recycled plastics will increase over time under the SCS and RES to reflect higher demand for recycled plastic driven by policy.

We then calculated the total net cost of waste management systems (opex plus capex minus revenues) for each year up to 2040. A discount rate of 3.5% was applied, and the present value of future cost streams between 2021 and 2040 was calculated for different scenarios to allow costs with different time profiles to be compared on a common basis. A discount rate of 3.5% was chosen following the Social Time Preference Rate (STPR) in real terms recommended in the UK government's Green Book (169). This rate is also considered reasonable by academic economists (e.g., 170, 171). We further evaluated the model outputs using discount rates of 0% and 7% to explore the sensitivity of results to the choice of discount rate.

Although all costs in the model are private costs associated with waste management systems, we further categorized these to who pays, either the public (e.g., government) sector or the private sector. We considered formal collection, formal sorting, incineration with energy recovery and landfill (both opex and capex) to be public sector costs while production, conversion, informal collection and all types of recycling are private sector costs. Plastic substitutes – namely paper, coated paper and compostables – were treated with the same logic and differentiated between public and private sector costs.

In calculating these costs, we assumed that high health, safety and environmental standards is the norm globally even though we recognize that today those standards are not always observed in parts of the world. This assumption was embedded in our cost data to help identify aspirational benchmarks for the world. We report all costs data as inflation adjusted (real) 2018 dollars (USD).

Specific data and assumptions associated with costs and revenues for different boxes within the system map are provided in Sections 16.2-16.11 below.

16.1 Growth Rates and Learning Curves

To account for the change in costs as a function of change in mass processed, we considered returns to scale separately from learning curves. Returns to scale are intended to get at potential increases in per-unit costs as mass flow increases, while learning curves evaluate how relative costs decrease based on mass. Both are calculated using the simplified formula based on Wagner (2014) (172).

$$C_t = C_{t-1}\left(\frac{K_t}{K_{t-1}}\right)^{-b} \qquad \text{Eq. (20)}$$

Where:

C_t is cost at time t;
K_t is the cumulative output at time t; and
b is the learning index.

While the learning index is assumed to be the same in every scenario, the mass that flows through each activity varies by scenario and, therefore, so does the final cost at time t.

As we only have data on output starting in 2016, we assumed that each industry’s cumulative output in 2016 was 10 times the 2016 output. This assumption was based on discussion with one of the authors of Farmer and Lafond (173). The learning index is log-normally transformed into the learning rate (LR) that denotes the relative cost decrease of a year-on-year doubling of output K. We assumed that returns to scale behave in a similar way to learning index, as it also reflects how costs change as a result of units produced.

$$LR = 1 - 2^{-b} \qquad \text{Eq. (21)}$$

We analyzed each box and arrow within the system map to determine if one or both of these concepts apply. The learning index by definition applies to all technologies, as each technology has a potential to become more efficient as a result of experience. Formal collection (Box C) is the only box where returns to scale apply; a clear relationship exists between the coverage rate of formal collection and average per unit costs, as expanding coverage rates to cover sparsely populated areas will increase average per unit costs. Existing data for formal collection in the EU yielded decreasing returns to scale of 25% (174). This assumption was not made in the HI archetype, where collection coverage already nears 100%. No other box was found to have systemwide returns to scale.

We were unable to find representative or up-to-date data sources for learning rates of the technologies relevant to this study. Instead, we looked for analogous technologies where learning rates were available, as technologies with similar characteristics tend to have corresponding learning rates:

1. Technologies whose capital costs make up a large proportion of total costs, such as manufacturing of cars or televisions (LR= 7-8%) (173); and
2. Technologies whose resource costs make up a large proportion of total costs, such as most energy industries (LR=0-5%) (173).

To be conservative we took the lower bound for both types of technologies for use in our analysis, 7% and 0% respectively. These assumptions were based on expert panel consensus. The learning rates across these categories tend to be stable over time (173). The petrochemical technologies covered by Farmer and Lafond only had data until the 1970s and were considered out-of-date by our expert panel. This was therefore excluded from the analysis.

We applied the first category (LR = 7%) to the capex and opex of the following parameters in the system map, as these face high capital costs and resemble the cost structures in manufacturing:

- Formal sorting (Box F);
- Closed loop MR (Box I);
- Open loop MR (Box J);
- Chemical recycling P2P (Arrow K1); and
- Chemical recycling P2F (Arrow K2).

Generally, it should be noted that mature technologies have had a large cumulative production to date and, hence, will not see major changes in per unit costs over time. However, this did not influence their progress rate itself. The following parameters were assumed to resemble the second category (LR = 0%), as they are either resource-intensive or have high labor costs (primarily informal collection):

- Formal collection (Box C);
- Incineration with energy recovery (Box O);
- Engineered landfill (Box N); and
- Informal collection (Box D).

16.2 Reduce Lever Costs

In calculating the costs of plastic reduction levers, we took into account end-of-life (EOL) costs. An overview of our approach is summarized in Table S58, with more detailed methodology below. The EOL costs were based on a waste ratio (i.e., the fraction of a unit weight of plastic that ends up as waste), which is intended to address the change in EOL needs given the reduced waste input.

The Reuse – consumer lever, which requires heavier reusable items to be produced and disposed of after a given number of reuses, was attributed a Waste Ratio of 35%. This was calculated as the weighted mean of three Waste Ratios of different item categories as laid out in the table below: carrier bags, diapers and food service disposables (Table S59). The weighting method was the same as the weighting for the cost calculation.

The Reuse – NDM lever was attributed a Waste Ratio of 12%. This was calculated as the mean of all identified case studies available for different models (Table S60).

The resulting life cycle costs per lever are shown in Table S61 below. To avoid double-counting of production and disposal costs it was necessary to account for any multi-use plastic that remained in the model and entered Box A.

16.3 Substitute Lever Costs

Substitute levers were attributed a cost per metric ton of plastic substituted with costs calculated separately for production and for EOL.

EOL Costs

EOL costs per metric ton of plastic substituted were calculated by summing collection, disposal and recycling/composting costs per metric ton of substitute material, and multiplying by an average weight factor increase of replacing plastic packaging with a substitute package of: 1.5 for paper or coated paper (175) and 1.3 for compostables (176). The underlying data to calculate costs for paper and coated paper are laid out in Table S62; those for compostables are in Table S63. Two key assumptions underlie our selected method. Firstly, that 100% of substitutes are collected, disposed of or recycled as managed waste, a conservative assumption so that EOL costs are not under-estimated. Secondly, cost per metric ton and % by waste treatment type remains constant over time in real terms, at 2016 levels.

16.4 Collection Costs

We “allocated” the cost of collection directly to plastics so that the costs in our system are attributable only to plastic waste. Our key assumption is that collection vehicles carrying plastics reach volumetric capacity before reaching mass-bearing capacity.

Because plastics typically occupy a large amount of space on waste collection vehicles, their cost per metric ton is higher than denser waste materials and MSW as a whole. This assumption appears to be reflected in the data, as plastics occupy up to half of the volume of a collection vehicle while contributing only around 10% of the mass (177). We used typical waste compositions observed on recyclate collection vehicles and residual waste collection vehicles reported by WRAP Cymru (177) and waste density data to calculate the space occupied by plastics on residual waste collection vehicles and dry recyclate collection vehicles. The sum of the volume occupied on collection vehicles by 'dense plastics,' 'plastic film' and 'recycling sacks' was multiplied by the mean collection costs for dry recyclates and residual waste to calculate the collection costs 'allocated for plastics' waste in both residual waste collection vehicles and dry recyclate collection vehicles.

We modeled this using typical bulk densities (Eq. 22):

$$\%VWcf_i = \frac{\frac{\%Wcf_i}{\rho Wcf}_i}{\sum \frac{\%Wcf_i}{\rho Wcf}_i} \qquad \text{Eq. (22)}$$

Where:

$\%VWcf_i$ is the proportion of specified waste categories (i) on a collection vehicle by volume;
$\%Wcf_i$ is the proportion of specified waste categories (i) of waste on a collection vehicle by mass; and
ρWcf_i is the density of each specified waste category(i).

The allocated cost of collection of plastic in residual waste ($\$Col_{P:RW}$) and dry recyclates ($\$Col_{P:DR}$) was weighted by the proportion of plastics collected for recycling in HI countries calculated in collection for recycling by the formal sector (19.51%) for HI countries and 0% in UMI, LMI and LI countries.

The formal collection and sorting costs ($/t) used in this model were drawn from the literature, and the costs were allocated using estimated collection costs from the World Bank (2018) (30), adjusted to 2018 USD. Rural and urban waste collection costs were then calculated by establishing the ratio between selected sources reported by Eunomia (174), which showed collection costs in rural areas to be approximately 35% greater in rural areas compared to urban areas. Opex was assumed to be 70% of the costs for collection across all archetypes, according to Kaza et al. (30). In the BL scenario we assumed collection costs will remain constant (Table S64).

We note that capex typically represented 30% of the collection cost per metric ton, and opex represented the remainder (174).

16.5 Sorting Costs

Allocating the cost burden of plastics to sorting operations is important, as they have a different impact compared to other materials. Although we found several sources that show the allocated costs (cost burden for plastics is approximately three times higher than those for the full suite of recyclables), these sources did not specify the method for doing so. The following reasons were suggested for this greater cost burden:

- Sorting is strongly influenced by the cost of machinery and labor, and these have been reported to be greater for plastics in comparison to other materials (177). Baling equipment (an expensive unit process in terms of capex and maintenance) is also heavily utilized due to the presence of plastics.
- Plastics represent ~50 - 70% of the storage burden for input and pre-baled sorted material while contributing just 15–20% of the mass (Section 16.4).
- Intermediate PRFs (plastics sorting facilities) are often used due to needs for additional sorting before recycling (35), adding to and potentially doubling basic materials recovery facility costs.
- If sorting is done manually, the mass collected per pick is significantly lower than other denser materials such as paper and glass (178).

We were unable to find robust estimates on sorting costs for UMI, LMI and LI archetypes. Therefore, we chose to use data available for HI sorting costs as the baseline and use the cost differentials in recycling as a proxy for the inter-archetype cost relationships. (Table S65).

Our model strategically made cost comparisons by assuming that the cost of collection, landfill and incineration with energy recovery per metric ton is the same for all plastic categories within an archetype. This assumption is not strictly accurate due to the different densities and caloric values of different material types but was considered important to ensure our model compares like-for-like costs.

16.6 Mechanical Recycling Costs

We determined capex and opex for both closed loop and open loop mechanical recycling plants based on expert panel consensus (Table S66).

Table S66 presents the resulting costs in $/t input. Please note that the costs shown are those that would adhere to high environmental, health and safety standards across all archetypes, even if those standards are not always observed globally today. We are aware that in practice there is high variance around these costs due to different technologies, systems and standards used.

16.7 Chemical Recycling Costs

Similar to mechanical recycling, we determined capex and opex for P2F and P2P chemical recycling plants based on expert panel consensus and through consultation with companies working on chemical conversion technologies (Table S67). These are immature technologies with limited, real world, industrial scale cost data available.

- Approx. total capex of USD 34M/USD 44M for UMI and LMI/HI; 22,000 t/year capacity; 20-year lifetime
- Costs assumed for pyrolysis technologies (not gasification or solvolysis)

The large difference in costs between the HI and the UMI and LMI archetypes in Table S67 is due to the higher labor and energy costs in the HI archetype. Costs were calculated assuming all recycling facilities adhere to high environmental, health and safety standards across all archetypes - even if such standards are not regularly observed today.

Furthermore, we are assuming the same costs for P2P and P2F due to similar boundary conditions: from input into a pyrolysis plant to output from a pyrolysis plant, which can be either lighter liquids (e.g., naphtha) or heavier liquids (e.g., diesel). The former is used in plastic production (recycling) and the latter further refined into fuels (a form of disposal similar to incineration with energy recovery).

Once the product is bought by a petrochemical company or a refinery to introduce into the normal plastic production or respectively fuel refining process, the cost is reflected in the virgin plastic production costs or leaves our system map. In the P2P route, we are aware that there may be another refining/cleaning step before the product from the pyrolysis plant can be introduced into a steam cracker. We excluded this step in cost calculations due to a lack of data availability.

16.8 Recyclate Sale Price from Mechanical Recycling and Chemical Conversion

We also identified the respective recyclate and pyrolysis oil/naphtha sale prices (Table S68) that allow for computation of end-to-end economics for each recycling technology. Prices are assumed to be constant under BAU 2040 as we keep the oil price constant in our model, which we expect to be the main driver of price changes in a BAU scenario. We also assumed that demand for recycled plastic will not increase significantly in BAU due to insufficient legislation and industry commitments. A summary of sales prices for different recycling routes can be seen in Table S68.

The closed loop sales prices are based on a blended price of high-value plastics (PET, HDPE and PP) and assumes clean, sorted, post-losses ready-for-market flakes or pellets.

Rationale for open loop sales prices are as follows:

- Archetype HI:
    - Virgin price minus 46%
- Archetype UMI:
    - Virgin price minus 49% (computed as HI minus 5%)
- Archetypes LMI/LI:
    - Virgin price minus 51% (computed as HI minus 10%)

We assumed a virgin plastic price of $1,500/t. Differences between archetypes are based on expert panel consensus.

For P2F, we assumed a wholesale diesel price of $0.53/liter and the same price across all archetypes as the output, pyrolysis oil, is a tradable commodity. We also assumed the same price for P2P due to similar boundary conditions as discussed above.

In the SCS and RES, we assumed recyclate prices to increase, primarily driven by high demand for recycled content and higher quality of recyclates due to design for recycling; we also expected recyclate prices to increase. The price assumptions and rationale outlined below are based on expert panel consensus (Table S69-Table S70).

16.9 Disposal Costs

Engineered landfills

We used the national disposal type statistics drawn from World Bank WaW 2.0 dataset (62) to estimate the proportion of waste disposed to engineered landfills. Historic trends were used to estimate changes in these proportions over time; most notable were high income countries where incineration with energy recovery is growing at the expense of landfill (driven by EU). To quantify the financial cost associated with engineered landfills, we estimated the opex and annualized capex costs across the different archetypes (Table S71). The CAGR of HI engineered landfill was calculated by taking the average CAGR of mass waste sent to engineered landfill in the US from 2000-2012. This was compared against the CAGR of engineered landfill in the EU by mass from 2006-2016. A weighted average based on total waste produced in HI countries was applied for the final CAGR figure.

To quantify the financial cost associated with engineered landfills, we estimated the opex and annualized capex costs across the different archetypes (Table S71), and then applied these $/t costs to the mass of material being disposed of this way.

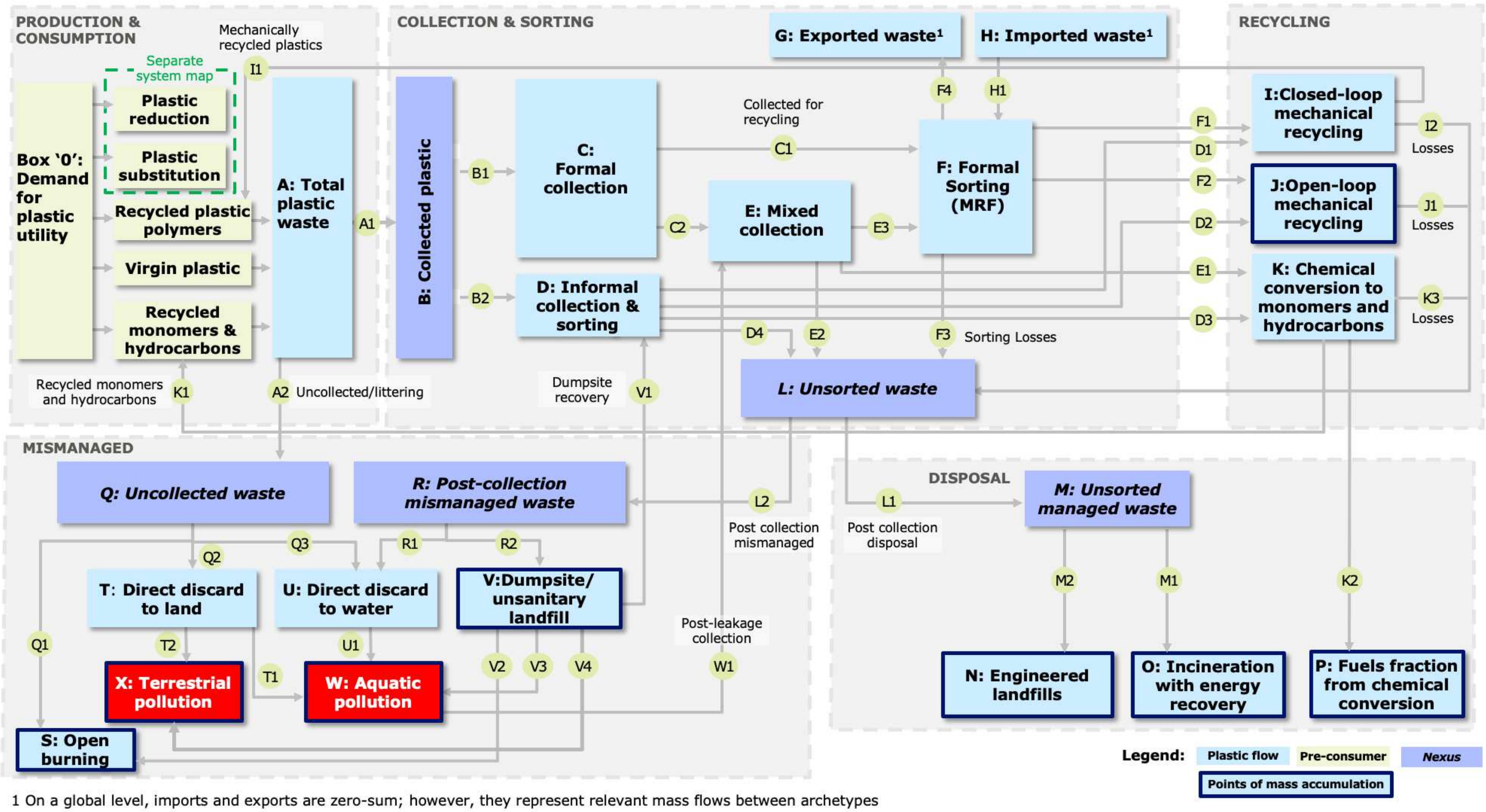
16.10 Incineration with energy recovery – Costs and Sale Prices

A proprietary model and proprietary data from expert panel member Jill Boughton were used to determine the opex and annualized capex costs of incineration with energy recovery as well as sale prices for the energy sold (Table S72).

Sale prices were given in $/t plastic input (Table S73-Table S74). Prices remain stable under BAU 2040 as we assume static electricity prices which are the main driver of price changes.

16.11 Recyclate Sale Prices

Based on the key enabling conditions above, especially high demand for recycled content and higher quality of recyclates due to design for recycling, we also expect recyclate prices to increase (Table S74-Table S75).



1 On a global level, imports and exports are zero-sum; however, they represent relevant mass flows between archetypes

Figure S1: Global plastic system map. The system map divides the global plastic system into five major components: production and consumption; collection and sorting; recycling; disposal; and mismanaged. Lettered boxes represent mass aggregation points in the model while arrows represent mass flows. Boxes with a bold outline represent places where plastic mass leaves the system, including terrestrial pollution (Box X) and aquatic pollution (Box W). Plastic demand is reflected in the boxes to the left of Box A. Plastic masses and flows were modeled for each geographic archetype and plastic category annually from 2016 to 2040. Mixed collection is defined as plastic that is collected for disposal or recovery rather than recycling. Detailed information on the data and assumptions underlying each box and arrow, as well as associated costs, are presented in Sections 7-14 and Section 16.

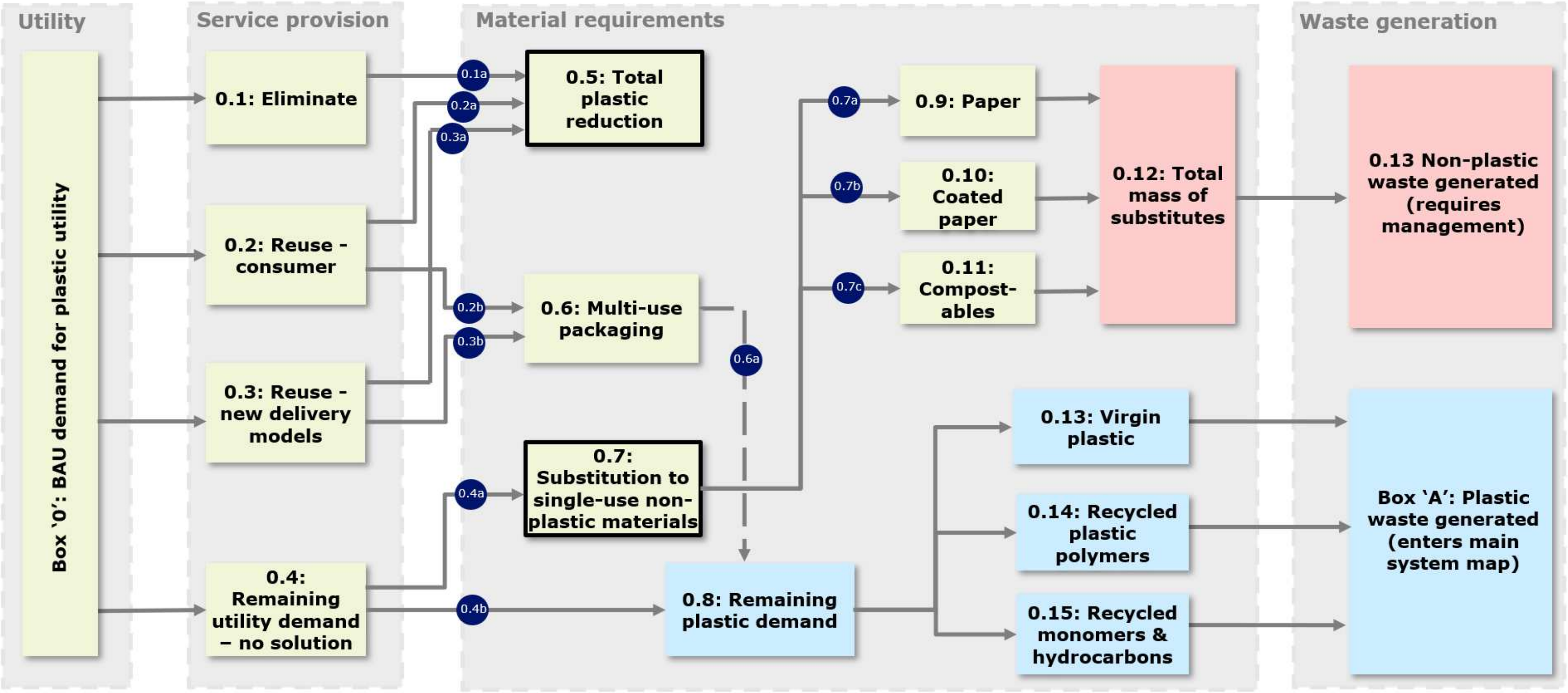
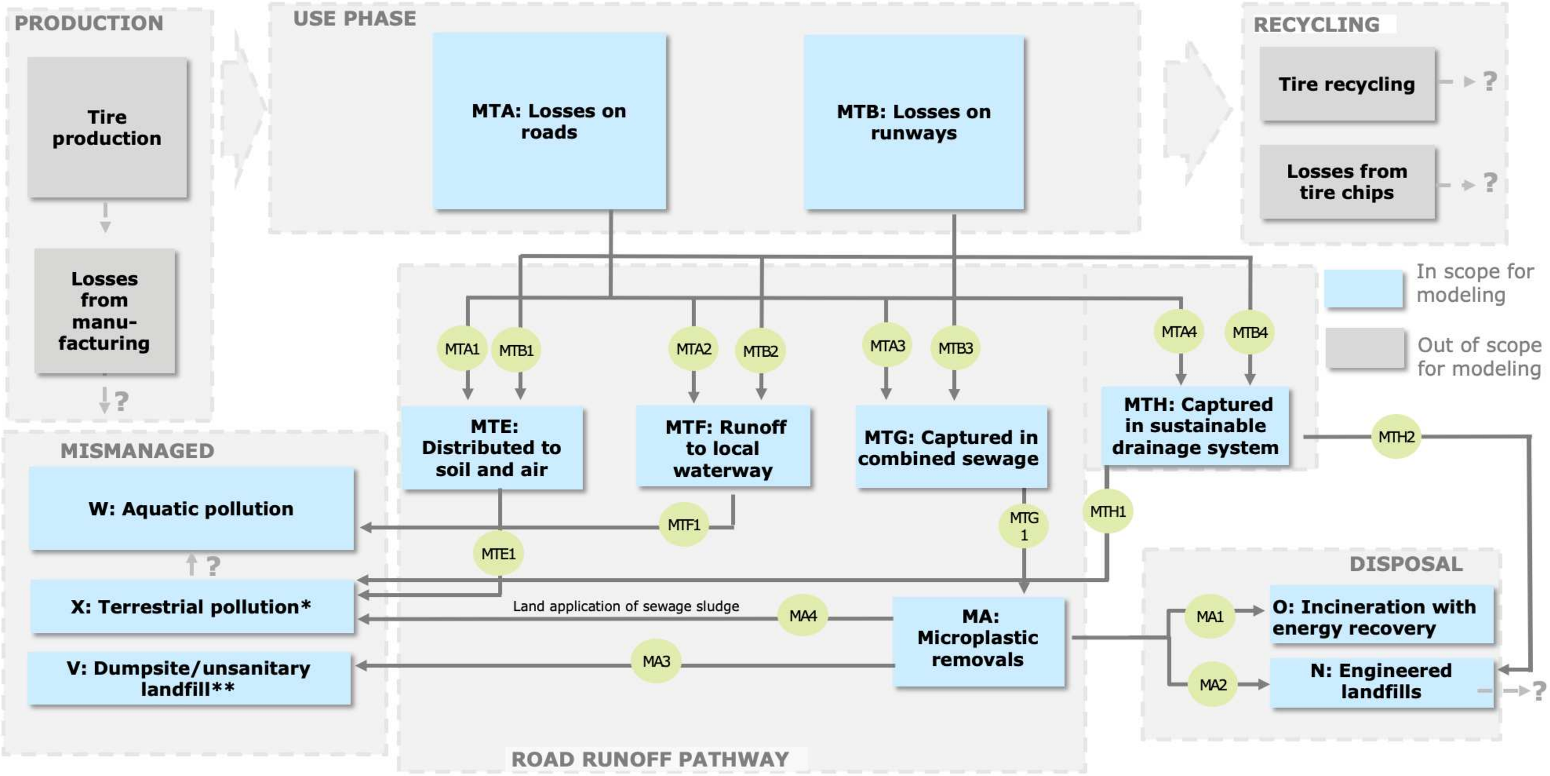


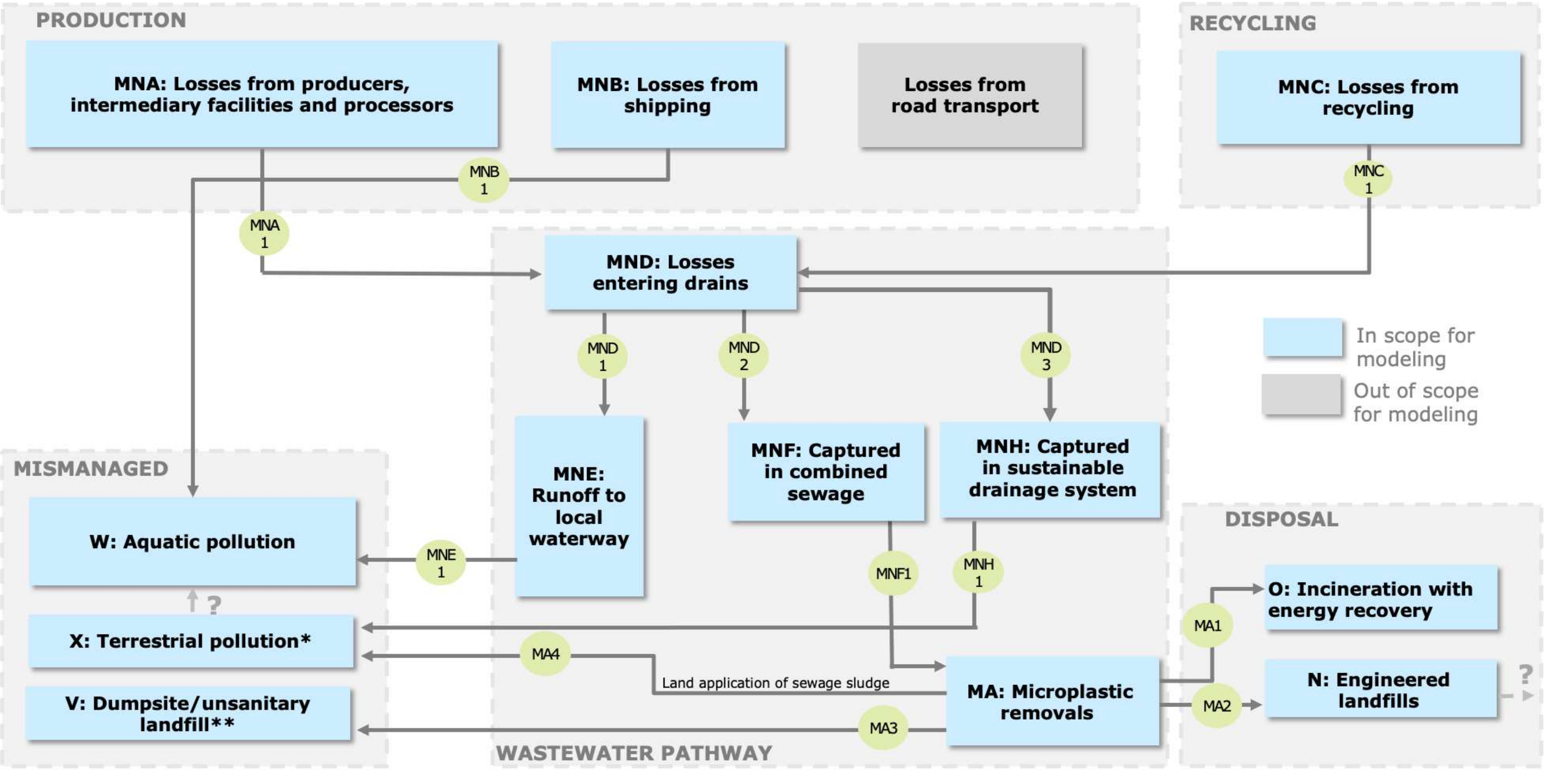
Figure S2: Subsystem map for plastic reduction and plastic substitution. The system map indicates flows of utility demand and supply (yellow boxes), plastic mass demand and supply (blue boxes) and substitute material mass (red boxes; not modeled). Outlined boxes (0.5 and 0.7) indicate where Business-as-Usual (BAU) demand for plastic mass accumulates in the system, such that utility in boxes 0.5, 0.7 and 0.8 sum to Box '0'; this Box '0' is the same as in Figure S1. The dotted arrow represents a partial flow, as only multi-use packaging for non-food applications was modeled as plastic. Boxes 0.1, 0.2 and 0.3 refer to the three reduce levers modeled. Detailed information on the data and assumptions underlying each box and arrow, as well as associated levers and costs, are presented in Section 9.



*includes both the application of sewage sludge to agricultural land and microplastics captured locally in "sustainable drainage systems"

** includes captured but unsafely disposed microplastic pollution

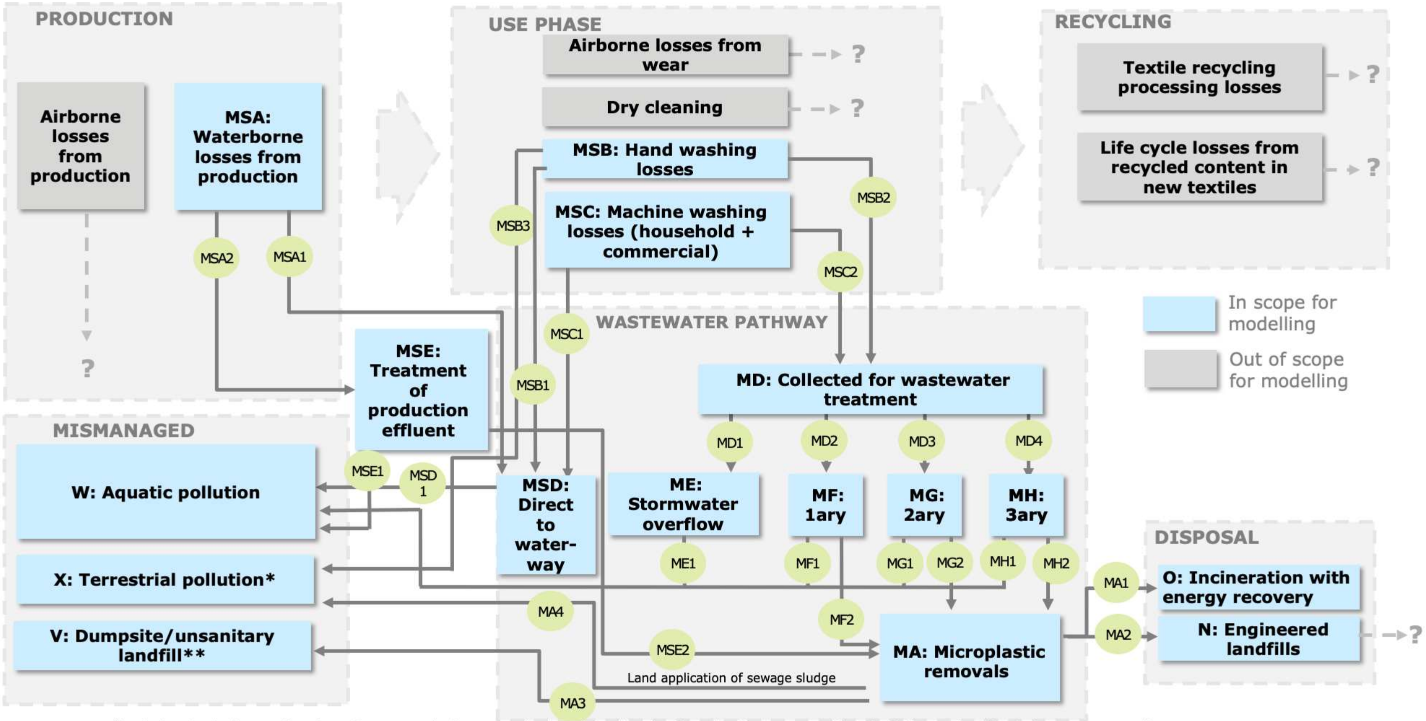
Figure S3: System map for tire-wear particles. Tire-wear particles (TWP) are particles released through mechanical abrasion of tires. Gray boxes were not modeled due to lack of data. See Table S49-Table S50 for detailed explanations of the data and assumptions underlying each box and arrow. Box MTA includes TWP generated by vehicles on urban, rural roads and motorways. Box MTB includes TWP generated by airplanes during takes-off and landings. Box MTE represents TWP distributed directly or via air to near road/runway soils. Box MTF represents TWP distributed directly to near road/runway waterways. Box MTG represents TWP distributed and removed by combined wastewater treatment plants. Box MTH represents TWP distributed to near roads/runway sumps filter systems. Box X includes both the application of sewage sludge to agricultural land and microplastics captured locally in sustainable drainage systems that are not safely disposed. Box V includes captured but unsafely disposed microplastics.



*includes both the application of sewage sludge to agricultural land and microplastics captured locally in "sustainable drainage systems"

** includes captured but unsafely disposed microplastic pollution

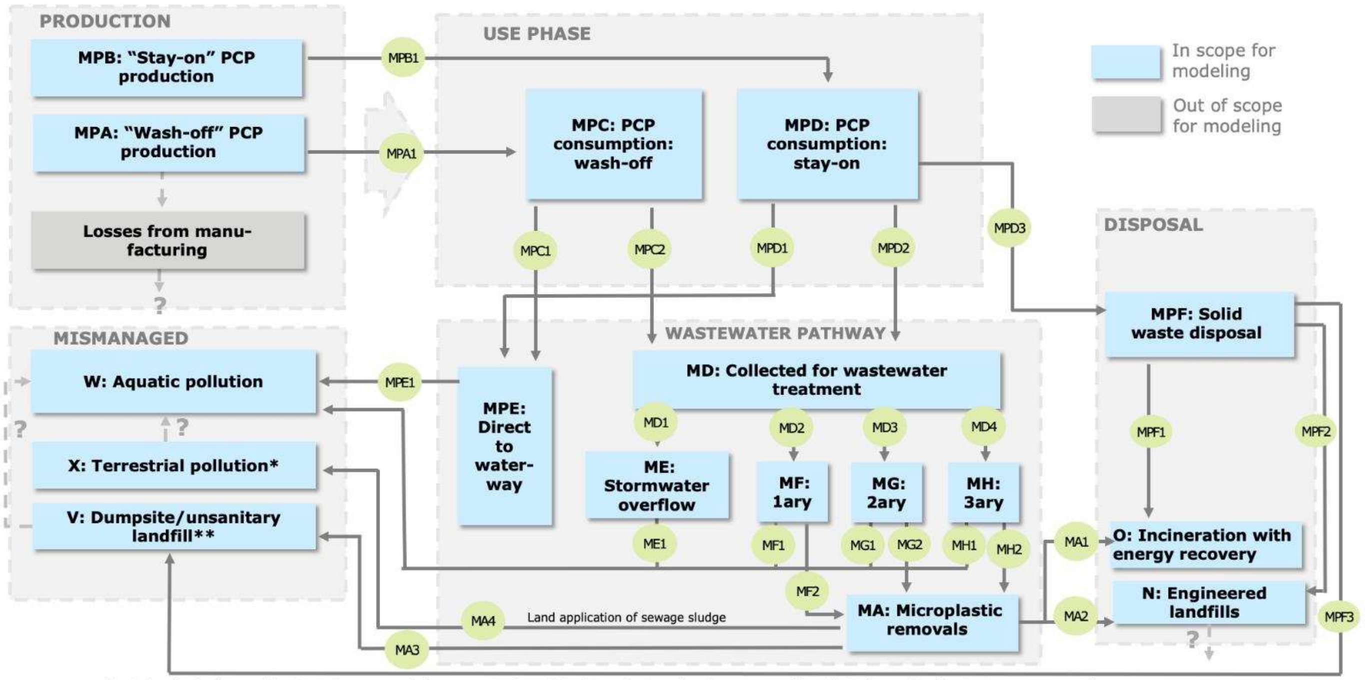
Figure S4: System map for plastic pellets. Plastic pellets are granules, usually shaped like a cylinder or disk, that are produced as a raw material or from recycled plastic and are used in the manufacture of plastic products. Gray boxes were not modeled due to lack of data. Section 15.4 and Table S56 contain detailed explanations of the data and assumptions underlying each box and arrow. Box MNA includes pellet loss in the plastic supply chain. Box MNB includes pellet loss during sea transport (loss of containers). Box MNC includes pellet loss during recycling. Box MND represents lost pellets distributed to indoor and outdoor drains. Box MNE represents pellets distributed directly to the sea near facilities waterways. Box MNF represents pellets distributed and removed by combined wastewater treatment plants. Box MNH represents pellets distributed to near facilities filter systems. Box X includes both the application of sewage sludge to agricultural land and microplastics captured locally in sustainable drainage systems. Box V includes captured but mismanaged plastic.



*includes both the application of sewage sludge to agricultural land and microplastics captured locally in "sustainable drainage systems"

** includes captured but unsafely disposed microplastic pollution

Figure S5: System map for synthetic textile microplastics. Microplastics from synthetic textiles are generated via shedding during production or use. Gray boxes were not modeled due to lack of data. Table S7 and Table S8 contain detailed explanations of the data and assumptions underlying each box and arrow. Box MSA represents microfibers released during textiles production. Box MSB represents microfibers released during handwashing of clothes within households. Box MSC represents microfibers released during household or commercial laundromats machine washing of clothes. Box MSD represents microfibers distributed directly to waterways via hand washing in rivers or wastewater without treatment. Box MSE represents microfibers distributed to wastewater treatments of textile producers. Box MD represents microfibers distributed to wastewater treatment facilities. Box MSD represents microfibers released from wastewater treatment facilities via overflows. Boxes MF, MG, and MH represent primary, secondary and tertiary wastewater treatment, respectively. Box X includes both the application of sewage sludge to agricultural land and microplastics captured locally in sustainable drainage systems. Box V includes captured but unsafely disposed microplastics**.**



*includes both the application of sewage sludge to agricultural land, and microplastics captured locally in "sustainable drainage systems"

** includes captured but unsafely disposed microplastic pollution

Figure S6: System map for personal care product (PCP) microplastics. PCP microplastics are added to PCPs intentionally by producers for a range of functions. Gray boxes were not modeled due to lack of data. See Section 15.4 and Table S56 for detailed explanations of the data and assumptions underlying each box and arrow. Box MPA represents wash-off PCPs (e.g., shampoos) production rate. Box MPB represents stay-on PCPs (e.g., make-ups) production rate. Box MPC represents wash-off PCP usage by consumers. Box MPD represents stay-on PCP usage by consumers. Box MPE represents microplastic ingredients from PCPs directly released to waterways via untreated wastewater. Box MPF represents microplastic ingredients in stay-on PCPs removed by cotton pads and disposed as solid waste. Box MD represents microfibers distributed to wastewater treatment facilities. Box ME represents microfibers released from wastewater treatment facilities via overflows. Boxes MF, MG, and MH represent primary, secondary and tertiary wastewater treatment, respectively. Box X includes the application of sewage sludge to agricultural land and microplastics captured locally in sustainable drainage systems. Box V includes captured but unsafely disposed microplastics. Treatment facilities, or municipal solid waste (MSW), may either be managed in engineered landfills or with thermal treatment with energy recovery, or be unmanaged in dumpsites/unsanitary landfills.

Table S1. Composition of the expert panel, affiliation, title, and working group participation.

Name	Affiliation	Title	Working Group
Richard Bailey	University of Oxford	Professor of Environmental Systems	Cross-cutting, modeling
Julien Boucher	Shaping Environmental Action	Co-Founder	Microplastics
Jill Boughton	Waste2Worth	Founder	Recycle and Dispose
Arturo Castillo	Imperial College	Research Fellow	Reduce and Substitute
Mao Da	Shenzhen Zero Waste	Executive Director	Recycle and Dispose
Enzo Favoino	Scuola Agraria del Parco di Monza	Researcher	Collect and Sort
Malati Gadgil	Independent	Independent Consultant	Collect and Sort
Linda Godfrey	Council for Scientific and Industrial Research	Professor	Collect and Sort
Jutta Gutberlet	University of Victoria	Professor	Collect and Sort
Edward Kosior	Nextek	Managing Director	Recycle and Dispose
Crispian Lao	Philippine Alliance for Recycling and Material Sustainability	Founding President	Recycle and Dispose
Daniela Lerario	Triciclos Brazil	(Previously CEO)	Collect and Sort
Ellie Moss	Encourage Capital	Senior Advisor	Reduce and Substitute
Ussif Rashid Sumaila	University of British Columbia	Professor and Canada Research Chair in Interdisciplinary Oceans and Fisheries Economics	Cross-cutting, economics
Daniella Russo	Think Beyond Plastics	Co-founder and Chief Executive Officer	Reduce and Substitute
Richard Thompson	University of Plymouth	Professor and Director of Marine Institute	Microplastics
Costas Velis	University of Leeds	Lecturer in Resource Efficiency Systems	Recycle and Dispose

Table S2. Expert panel workshops.

Location	**Dates**
London, UK	July 9-10, 2018
Washington, DC, USA	November 19-20, 2018
Hanoi, Vietnam	March 5-7, 2019
London, UK	July 9-11, 2019

Table S3: Estimated populations living in proximity to rivers or coastal waters.

Archetype	Number of people living in proximity to water		Proportion of population living in proximity to water	
	< 1 km	**> 1 km**	**< 1 km**	**> 1 km**
HI-U	387,364,176	502,326,123	43.5%	56.5%
HI-R	139,551,400	200,098,923	41.1%	58.9%
UMI-U	738,055,814	953,720,947	43.6%	56.4%
UMI-R	333,681,550	481,968,707	40.9%	59.1%
LMI-U	957,825,466	1,115,472,519	46.2%	53.8%
LMI-R	340,003,878	470,101,017	42.0%	58.0%
LI-U	91,908,375	136,868,144	40.2%	59.8%
LI-R	159,418,874	278,735,508	36.4%	63.6%

Table S4: Data Pedigree Scoring Matrix.

Score	1	2	3	4
Sample size	Representative	Representative under certain conditions and/or in some scenarios	Limited representation: only representative under a specific condition or in one scenario	Unknown
Uncertainty	Uncertainty is measured and reported (e.g., standard deviation, confidence interval, interquartile range, mean, error bars)	Uncertainty is not measured nor reported, but all assumptions are stated and the impacts of assumptions on results are discussed.	Assumptions are stated, but no reference is made to the impact of assumptions on results.	Uncertainty and assumptions are neither measured nor discussed
Accuracy and reliability	Verified based on empirical measurements and/or direct-to-source interviews (e.g., cost data quoted directly from a recycling facility will be graded as 1 in this category).	Verified data based on empirical measurements and or direct-to-source interviews with some assumptions and/or estimates to fill data gaps.	Non-verified data based on estimates and/or assumptions including qualified estimates (e.g., expert opinion).	Non-verified and/or non-qualified data.
Date of publication	<5 years ago	<10 years ago	<15 years ago	>15 years ago and/or unknown

Table S5: Uncertainty by data pedigree score.

Data Pedigree Level	Data Pedigree Score	Uncertainty
1	4-5	± 10%
2	6-8	± 20%
3	9-12	± 35%
4	13-16	± 50%

Table S6: Data pedigree level assignments for model inputs per Table S5. The scenarios are: BAU, Current Commitments (CCS), Collect and Dispose (CDS), Recycling (RES), Reduce and Substitute (RSS), and System Change (SCS). NA= not applicable (i.e., input not modeled in the scenario). TS = target state without associated uncertainty. Plug = A flow (arrow) which is the resultant flow after other flows from a stock (box) have been accounted for and therefore has no uncertainty associated with the flow itself. Where data pedigree level differs between high-income archetypes and middle- and low-income archetypes, the first number represents the data pedigree for HI and the second for the other archetypes. Zone A = < 1 km to water. Zone B = > 1 km to water.

Flow	**Box/ Arrow**	**Units**	**Scenario**					
			BAU	**CCS**	**CDS**	**RES**	**RSS**	**SCS**
Reduce and Substitute								
Reduce potential - Eliminate	Box 0.1	%	NA	4	4	4	TS	TS
Reduce potential - Reuse	Box 0.2	%	NA	NA	NA	NA	TS	TS
Reduce potential - New delivery models (NDM)	Box 0.3	%	NA	NA	NA	NA	TS	TS
Substitute potential - Paper	Box 0.9	%	NA	NA	NA	NA	TS	TS
Substitute potential - Coated paper	Box 0.10	%	NA	NA	NA	NA	TS	TS
Substitute potential - Compostables	Box 0.11	%	NA	NA	NA	NA	TS	TS
Shift from multi to rigid	NA	%	NA	NA	NA	TS	NA	TS
Shift from multi to flexible	NA	%	NA	4	4	TS	4	TS
Shift from flexible to rigid	NA	%	NA	NA	NA	TS	NA	TS
Collection and Sorting								
Average archetype collection rates	A1	%	1	1	TS	TS	1	TS
Uncollected waste	A2	%	Plug	Plug	Plug	Plug	Plug	Plug
Total formal collection	B1	t/y	Plug	Plug	Plug	Plug	Plug	Plug
Total informal household and street collection	Arrow B2	t/y	3	3	3	3	3	TS
Share of formal collected for recycling (separated at source)	Arrow C1	%	2	4*/2	4*/2	TS/2	4*/2	TS/2
Share of formal to mixed collection	Arrow C2	%	Plug	Plug	Plug	Plug	Plug	Plug
Mass of mixed waste to chemical conversion (as % of Box C)	Arrow E1	%	3/4	3/4	3/4	3/4	3/TS	3/4
Share of mixed waste to losses	Arrow E2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of mixed waste to dirty MRF	Arrow E3	%	NA	NA	NA	TS	NA	TS
Share of informal sector to closed loop	Arrow D1	%	4	4	4	TS	4	TS

Flow	Box/ Arrow	Units	Scenario					
			BAU	CCS	CDS	RES	RSS	SCS
Share of informal sector to open loop	Arrow D2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of informal sector to chemical conversion	Arrow D3	%	4	4	4	TS/4	4	TS/4
Share of informal sector to losses	Arrow D4	%	4	4	4	4	4	4
Share of sorted waste to closed loop	Arrow F1	%	1/4	1/4	1/4	TS	1/4	TS
Share of sorted waste to open loop	Arrow F2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of sorted waste to losses	Arrow F3	%	2	2	2	TS	2	TS
Import-Export								
Total exported waste	Arrow F4 / Box G	t/y	3	3	TS	3	TS	TS
Total imported waste	Arrow H1 / Box H	t/y	3	3	TS	3	TS	TS
Recycling								
Share of closed loop actually recycled	Arrow I1	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of closed loop to losses	Arrow I2	%	2/3	2/3	2/3	TS	2/3	TS
Share of open loop actually recycled	Arrow J0	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of open loop to losses	Arrow J1	%	2/3	2/3	2/3	TS	2/3	TS
Share of chemical to plastic	Arrow K1	%	4	4	4	TS	4	TS
Share of chemical to losses	Arrow K3	%	2/3	2/3	2/3	TS	2/3	TS
Disposal								
% Managed waste from post-collection waste	Arrow L1	%	2	2	TS	2	2	TS
% Managed waste lost as mismanaged waste	Arrow L2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of managed to incineration with energy recovery	Arrow M1 / Box O	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of managed to engineered landfills	Arrow M2 / Box N	%	2	2	2	2	2	2
Share of chemical to fuel	Arrow K2	%	Plug	Plug	Plug	Plug	Plug	Plug

Flow	Box/ Arrow	Units	Scenario					
			BAU	CCS	CDS	RES	RSS	SCS
Mismanaged Waste								
Share uncollected to open burn	Arrow Q1	%	4	4	4	4	4	4
Share uncollected to terrestrial dumping (Zone A)	Arrow Q2 (Zone A)	%	Plug	Plug	Plug	Plug	Plug	Plug
Share uncollected to terrestrial dumping (Zone B)	Arrow Q2 (Zone B)	%	Plug	Plug	Plug	Plug	Plug	Plug
Share uncollected discarded direct to water (Zone A)	Arrow Q3 (Zone A)	%	4	4	4	4	4	4
Share uncollected discarded direct to water (Zone B)	Arrow Q3 (Zone B)	%	4	4	4	4	4	4
Share of terrestrial dumping to aquatic pollution (Zone A)	Arrow T1 (Zone A)	%	4	4	4	4	4	4
Share of terrestrial dumping to aquatic pollution (Zone B)	Arrow T1 (Zone B)	%	4	4	4	4	4	4
Share of terrestrial dumping to terrestrial pollution	Arrow T2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share post-collection mismanaged discarded direct to water	Arrow R1	%	4	4	4	4	4	TS
Share post-collection mismanaged to dumpsite or unsanitary landfill	Arrow R2	%	Plug	Plug	Plug	Plug	Plug	Plug
Dumpsite recovery	Arrow V1	t/y	3	3	3	3	3	3
Share of dumpsite/unsanitary landfill to open burn	Arrow V2	%	4	4	4	4	4	4
Share of dumpsite/unsanitary landfill to aquatic pollution (Zone A)	Arrow V3 (Zone A)	%	4	4	4	4	4	4
Share of dumpsite/unsanitary landfill to aquatic pollution (Zone B)	Arrow V3 (Zone B)	%	4	4	4	4	4	4
Share of dumpsite/unsanitary landfill to terrestrial pollution	Arrow V4	%	4	4	4	4	4	4
Post-pollution collection (beach clean ups)	Arrow W1	%	2	2	2	2	2	2

Flow	Box/ Arrow	Units	Scenario					
			BAU	CCS	CDS	RES	RSS	SCS

*Only for High-income Urban archetype. High-income Rural Archetype same as Middle and Low-income archetypes.

Table S7: Categories of system interventions conceptualized for constructing scenarios.

Intervention	Description/Examples	Applicable Wedge(s)
1. Reduce overall plastic in the system	Eliminate unnecessary uses of plastic, NDM and reuse models	Reduce
2. Substitute plastics with alternative materials	Substitute plastic with paper, glass and other biodegradable materials	Substitute
3. Increase collection capacity	Increase collection by the formal sector through incentives and government policies, and reduce post-collection leakage	Recycle, Dispose
4. Design for recycling	Redesign of materials, products and system to improve the economics and amount of recycling	Recycle
5. Scale sorting and mechanical recycling capacity	Increase the capacity of mechanical recycling globally and the share of plastic collected for recycling (separated at source)	Recycle
6. Scale chemical conversion capacity	Plastics-to-plastics conversion	Recycle
7. Reduce post-collection leakage	Build landfill and incinerators (including non-conventional thermal treatment, NCTT, and related plastic-to-fuel options) as a last resort for non-recyclable plastic	Dispose
8. Reduce import and export of plastic waste	Reduce exports from low-leakage to high-leakage countries	Recycle, Dispose

Table S8: Scenario construction based on specific and relevant application of the system interventions described in Table S7.

Scenario	**System Interventions and Actions Applied to BAU**
Baseline scenarios	
Scenario I – Business as Usual (BAU)	None
Scenario 2 – Current Commitments (CCS)	Fully implement 2016-2019 government policy and industry commitments
Post-consumption ("Downstream") scenarios	
Scenario 3 – Collect and Dispose (CDS)	Intervention 4: Increase collection capacity Intervention 7: Reduce post-collection leakage; increase landfill and incineration with energy recovery Intervention 8: Reduce exports from low-leakage to high-leakage countries From CCS: Implement 2016-2019 government policy and industry commitments
Scenario 4 – Recycling (RES)	Intervention 3: Design for recycling Intervention 4: Increase collection capacity Intervention 5: Scale sorting and mechanical recycling capacity Intervention 6: Scale chemical conversion capacity From CCS: Implement 2016-2019 government policy and industry commitments
Pre-consumption ("Upstream") scenarios	
Scenario 5 – Reduction and Substitution (RSS)	Intervention 1: Reduce plastic use Intervention 2: Increase substitution of plastic Intervention 8: Reduce exports from low-leakage to high-leakage countries From CCS: Implement 2016-2019 government policy and industry commitments
Integrated scenario	
Scenario 6 – System Change (SCS)	Interventions 1- 8 (as stated above in Scenarios 3-5) From CCS: Implement 2016-2019 government policy and industry commitments

Table S9: Framework for parameterization of stocks (boxes) and flows (arrows) in the system map (Figure S1) by scenario. NA= not applicable (i.e., input not modeled in the scenario. BL for baseline BAU conditions, CCS for assessment of future implementation of government and industry commitments, and MFA for maximally foreseen assessment of the implementation or growth rates of relevant actions under each of the nine system interventions driving each scenario (see Table S5 and Table S6). A flow (arrows), which is the resultant flow after other flows from a stock (box) have been accounted for, is marked as "plug". For some arrows, the values are differentiated by plastic category: RM = rigid monosmaterial, FM= flexible monomaterial, and MM = multimaterial/multilayer. Zone A = < 1 km to water. Zone B = > 1 km to water.

Parameter	**Box/ Arrow**	**Units**	**Scenario**					
			BAU	**CCS**	**CDS**	**RES**	**RSS**	**SCS**
Reduce and Substitute								
Reduce potential - Eliminate	Box 0.1	%	NA	CC	CC	CC	MFA	MFA
Reduce potential - Reuse	Box 0.2	%	NA	NA	NA	NA	MFA	MFA
Reduce potential - NDM	Box 0.3	%	NA	NA	NA	NA	MFA	MFA
Substitute potential - Paper	Box 0.9	%	NA	NA	NA	NA	MFA	MFA
Substitute potential - Coated paper	Box 0.10	%	NA	NA	NA	NA	MFA	MFA
Substitute potential - Compostables	Box 0.11	%	NA	NA	NA	NA	MFA	MFA
Shift from multimaterial to rigid monomaterial	NA	%	NA	NA	NA	MFA	NA	MFA
Shift from multimaterial to flexible monomaterial	NA	%	NA	CC	CC	MFA	CC	MFA
Shift from flexible monomaterial to rigid monomaterial	NA	%	NA	NA	NA	MFA	NA	MFA

Parameter	**Box/ Arrow**	**Units**	**Scenario**					
			BAU	**CCS**	**CDS**	**RES**	**RSS**	**SCS**
Collect and Sort								
Average archetype collection rates	A1	%	BL	BL	MFA	MFA	BL	MFA
Uncollected waste	A2	%	Plug	Plug	Plug	Plug	Plug	Plug
Total formal collection	B1	t/y	Plug	Plug	Plug	Plug	Plug	Plug
Total informal household and street collection	Arrow B2 / Box D	t/y	BL	BL	BL	BL	BL	MFA
Share of formal collected for recycling (separated at source)	Arrow C1	%	BL	CC	BL	MFA	CC	MFA
Share of formal to mixed collection	Arrow C2	%	Plug	Plug	Plug	Plug	Plug	Plug
Mass of mixed waste to chemical conversion	Arrow E1	%	BL	BL	BL	MFA	BL	MFA
Share of mixed waste to losses	Arrow E2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of mixed waste to dirty MRF	Arrow E3	%	BL	CC	CC	CC	CC	CC
Share of informal sector to closed loop mechanical recycling	Arrow D1	%	BL	BL	BL	MFA	BL	MFA
Share of informal sector to open loop mechanical recycling	Arrow D2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of informal sector to chemical conversion	Arrow D3	%	BL	BL	BL	MFA	BL	MFA
Share of informal sector to losses	Arrow D4	%	BL	BL	BL	BL	BL	BL
Share sorted waste to closed loop mechanical recycling	Arrow F1	%	BL	BL	BL	MFA	BL	MFA

Parameter	Box/ Arrow	Units	Scenario					
			BAU	CCS	CDS	RES	RSS	SCS
Share sorted waste to open loop mechanical recycling	Arrow F2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share sorted waste to losses	Arrow F3	%	BL	BL	BL	MFA	BL	MFA
Import-Export								
Total exported waste	Arrow F4 / Box G	t/y	BL	BL	RM=MFA	BL	RM=MFA	RM=MFA
Total imported waste	Arrow H1 / Box H	t/y	BL	BL	RM=MFA	BL	RM=MFA	RM=MFA
Recycling								
Share of closed loop mechanical recycling actually recycled	Arrow I1	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of closed loop mechanical recycling to losses	Arrow I2	%	BL	BL	BL	MFA	BL	MFA
Share of open loop mechanical recycling actually recycled	Arrow J0	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of open loop mechanical recycling to losses	Arrow J1	%	BL	BL	BL	MFA	BL	MFA
Share of chemical conversion to plastic	Arrow K1	%	BL	BL	BL	MFA	BL	MFA
Share of chemical conversion to losses	Arrow K3	%	BL	BL	BL	MFA	BL	MFA
Disposal								
% Managed waste from post-collection waste	Arrow L1	%	BL	BL	MFA	BL	BL	MFA
% Managed waste lost as mismanaged waste	Arrow L2	%	Plug	Plug	Plug	Plug	Plug	Plug

Parameter	Box/ Arrow	Units	Scenario					
			BAU	CCS	CDS	RES	RSS	SCS
Share of managed to engineered landfills	Arrow M2 / Box N	%	BL	BL	BL	BL	BL	BL
Share of managed waste to incineration with energy recovery	Arrow M1 / Box O	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of chemical conversion to fuels	Arrow K2 / Box P	%	Plug	Plug	Plug	Plug	Plug	Plug
Mismanaged Waste								
Share of uncollected waste to open burn	Arrow Q1	%	BL	BL	BL	BL	BL	BL
Share of uncollected waste to terrestrial dumping (Zone A)	Arrow Q2 (Zone A)	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of uncollected waste to terrestrial dumping (Zone B)	Arrow Q2 (Zone B)	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of uncollected waste discarded direct to water (Zone A)	Arrow Q3 (Zone A)	%	BL	BL	BL	BL	BL	BL
Share of uncollected waste discarded direct to water (Zone B)	Arrow Q3 (Zone B)	%	BL	BL	BL	BL	BL	BL
Share of terrestrial dumping to aquatic pollution (Zone A)	Arrow T1 (Zone A)	%	BL	BL	BL	BL	BL	BL
Share of terrestrial dumping to aquatic pollution (Zone B)	Arrow T1 (Zone B)	%	BL	BL	BL	BL	BL	BL
Share of terrestrial dumping to terrestrial pollution	Arrow T2	%	Plug	Plug	Plug	Plug	Plug	Plug
Share of post-collection mismanaged discarded direct to water	Arrow R1	%	BL	BL	BL	BL	BL	MFA
Share of post-collection mismanaged to dumpsite or unsanitary landfill	Arrow R2	%	Plug	Plug	Plug	Plug	Plug	Plug
Dumpsite recovery	Arrow V1	t/y	BL	BL	BL	BL	BL	BL

Parameter	Box/ Arrow	Units	Scenario					
			BAU	CCS	CDS	RES	RSS	SCS
Share of dumpsite/unsanitary landfill to open burn	Arrow V2	%	BL	BL	BL	BL	BL	BL
Share of dumpsite/unsanitary landfill to aquatic pollution (Zone A)	Arrow V3 (Zone A)	%	BL	BL	BL	BL	BL	BL
Share of dumpsite/unsanitary landfill to aquatic pollution (Zone B)	Arrow V3 (Zone B)	%	BL	BL	BL	BL	BL	BL
Share of dumpsite/unsanitary landfill to terrestrial pollution	Arrow V4	%	BL	BL	BL	BL	BL	BL
Post-pollution collection (beach clean ups)	Arrow W1	%	BL	BL	BL	BL	BL	BL

Table S10: Populations and compound annual growth rate (CAGR) by archetype.

Archetype		Total Population (in millions)			Calculated CAGR
		2016	2030	2040	
Urban	HI	961.98	1,048.88	1,099.74	0.56%
	UMI	1,693.42	2,068.83	2,223.59	1.14%
	LMI	1,195.99	1,687.76	2,096.76	2.37%
	LI	206.74	358.85	514.93	3.88%
Rural	HI	223.88	201.02	175.94	-1.00%
	UMI	913.13	698.42	579.15	-1.88%
	LMI	1,816.44	1,907.04	1,865.34	0.11%
	LI	452.53	577.06	651.23	1.53%

Table S11: Estimated annual total plastic waste generation projections and calculated compound annual growth rates (CAGR) by archetype.

Archetype		**Total annual plastic waste generated (Mt)**			**Calculated CAGR**
		2016	**2030**	**2040**	
Urban	HI	72.759	90.291	104.194	1.51%
	UMI	53.272	104.688	143.703	4.22%
	LMI	25.492	48.792	70.624	4.33%
	LI	3.801	10.065	17.237	6.58%
Rural	HI	16.933	17.304	16.670	-0.07%
	UMI	19.150	23.561	24.952	1.11%
	LMI	19.358	27.565	31.415	2.04%
	LI	4.160	8.093	10.900	4.18%
Global		214.926	330.360	419.695	2.83%

Table S12: Data sources and methodology used to estimate UK plastic municipal solid waste (MSW) composition by plastic category.

Plastic category	Product type	Mass of plastic MSW 2016 (t)	% of plastic MSW	Source and methodology
Rigid monomaterial	Bottles	557,033	15.13%	RF/Defra 2013 (72), scaled to a UK-wide estimate and corrected to 2019 based on UK total plastic waste generated over time (179)
	Food service disposables	164,054	4.45%	Calculated from data on number and mass of food service disposables from: WWF / Eunomia (180); Defra 2018 (181); and ICF/Eunomia 2018 (182)
	Other dense plastic packaging	818,595	22.23%	RF/Defra 2013 (72), scaled as above
	B2B packaging	143,171	3.89%	Retail, hospitality, public institutions and other services' portion of (73).
	Household goods	259,173	7.04%	All remaining non-packaging dense plastic waste reported in RF/Defra 2013 (72) after removing food service disposables, assuming 50% is rigid monomaterial (explanation in-text)
Flexible monomaterial	Carrier bags	151,667	4.12%	Carrier bags mass in 2017 (120), adjusted to pre-bag-ban levels of demand
	Films	582,661	15.82%	RF/Defra 2013 (72), after removing carrier bag mass and multimaterial film bags
	B2B films	141,214	3.83%	WRAP 2018 (120) Portion of non-consumer film, produced by hospitality and retailers only (excludes agricultural film packaging etc.)
Multimaterial/multilayer	Sachets and multimaterial	145,665	3.96%	RF/Defra 2013 (72), non-bag multimaterial film packaging plus multimaterial portion of other film-based bags
	Laminated paper and aluminum	55,790	1.51%	Calculated sum of the plastic component in 1) laminated paper, assuming 50% of RF/Defra 2013 (72) "other - non-recyclable" card and paper is laminated; 2) laminated aluminum (39); 3) laminated cartons - collection of food and drink cartons at the curbside (183)
	Household goods	579,195	15.73%	RF/Defra 2013 (72), remainder of the non-packaging plastic waste not allocated to other rows
	Diapers and hygiene (plastic portion)	84,428	2.29%	Sum of the plastic components in 1) disposable nappies, sanitary products and dressings from RF/Defra 2013 (72) assuming 7.5% plastic (184); and 2) calculated mass based on units sold and unit mass for wet wipes (180) and cotton buds (181, 182).
	TOTAL	3,682,647	100%	

Table S13: Allocation of material types reported in waste data into plastic categories.

Plastic material reported	**Percent Allocation to plastic categories (source)**
“Dense packaging” or “rigid”	100% monomaterial (185)
“Other”	50% rigid monomaterial 50% multimaterial/multilayer
Films	80% monomaterial 20% multimaterial (186)
“Cartons”	18% polyethylene (PE) (average of 15% for chilled cartons (180), 20% for aseptic cartons (180), and 20% for laminated cartons (184))
Sanitary items and diapers	7.5% plastic (187)
Polyvinyl chloride (PVC)	50% rigid (e.g., toys, strollers, rigid packaging boxes) 50% flexible (e.g., sheeting, shrink wrap, cling film, labels)

Table S14: Categorization and allocation of municipal solid waste (MSW) by product application and archetype. B2B = business to business.

Plastic type	Product application	High income[5-18]		LI/LMI/UMI[19-23]	
		% of total MSW (2016)	Product application as a % of plastic type (2016)	% of total MSW (2016)	Product application as % of plastic type (2016)
Rigid monomaterial	Water bottles	1%	2%	1%	2%
	Other food-grade bottles	8%	15%	5%	15%
	Non-food-grade bottles	6%	11%	4%	11%
	Food service disposables	4%	8%	3%	8%
	Pots, tubs and trays	8%	15%	5%	15%
	B2B packaging	4%	7%	2%	7%
	Household goods	7%	13%	4%	13%
	Other rigid monomaterial packaging	14%	27%	9%	27%
Flexible monomaterial	Carrier bags	4%	17%	8%	17%
	Films	16%	67%	30%	67%
	B2B films	4%	16%	7%	16%
Multimaterial/ multilayer	Sachets and multilayer flexibles	4%	17%	18%	80%
	Laminated paper and aluminum	2%	6%	0%	1%
	Household goods [multimaterial]	16%	67%	2%	9%
	Diapers and hygiene (plastic portion)	2%	10%	2%	10%

Table S15: Plastic waste proportion by plastic category and archetype.

Plastic Category	**HI-U, HI-R** (72–75)	**UMI-U, UMI-R, LMI-U, LMI-R, LI-U, LI-R** (79–83)
Rigid monomaterial	53%	33%
Flexible monomaterial	24%	45%
Multimaterial/multilayer	23%	22%

Table S16. Proportion of packaging by plastic type and archetype.

Plastic Category	**HI**	**UMI/LMI/LI**
Rigid monomaterial	87%	87%
Flexible monomaterial	83%	83%
Multimaterial/multilayer	23%	81%

Table S17. Reduction of plastic by type from corporate commitments by archetype.

Plastic Category	**HI**	**UMI/LMI/LI**
Rigid monomaterial	1.3%	1.3%
Flexible monomaterial	1.2%	1.2%
Multimaterial/multilayer	0.3%	1.2%

Table S18. Estimated percent change by archetype from multimaterial/multilayer plastic to flexible monomaterial due to corporate New Plastic Economy Global Commitment.

Income Group	Percent Change
HI	4.7%
UMI/LMI/LI	16.2%

Table S19: Reduce and substitute levers modeled.

Intervention	**Lever**	**Definition**
I. Reduce	1. Eliminate	Decreasing the use of plastic without substituting to any other material, via for example: redesigning product: reducing overpackaging; reducing demand through bans, fees and incentive systems; extending product life or sharing solutions; and increasing utility per package or product virtualization.
	2. Reuse (consumer)	Switching single-use plastics to reusable items owned and managed by the user, without the need for new services or businesses.
	3. Reuse (New Delivery Model)	Switching from single-use plastics to reusable items requiring new businesses or take-back services, such as: refill services, dispensers, leased packaging and product shift to services and e-commerce.
II. Substitute	4. Paper	Wood pulp-based or other fiber-based paper material, sourced from virgin or recycled material.
	5. Coated paper	Paper with a coating of maximum 5% by weight, ideally tear-off/peelable or one-sided laminates with weak adhesives to facilitate acceptance in paper recycling streams (188). Our scenarios add <0.3% coating by mass of paper production of 415 Mt per year (189), which we assume is tolerable, but further research is needed to confirm maximum allowable volumes of coated paper.
	6. Compostables	Certified compostable products capable of disintegrating into natural elements in a home or industrial composting environment, within a specified number of weeks, leaving no toxicity in the soil.

Table S20: Categorization of municipal solid waste (MSW) data by 15 product applications and assessment of the relevance of the reduction and substitution levers to each product category. NDM = new delivery model. B2B = business to business.

Plastic Category	Product application	Product sub-category	Eliminate	Reuse	NDM	Paper	Coated paper	Compostable
Rigid monomaterial	Water bottles	Still water only, including bottle tops		x	x			
	Other food-grade bottles	Target market for refill (milk, soda, sparkling water)			x			
		Remainder (juice, concentrates, sports drinks, etc.)						
	Non-food-grade bottles	Non-food bottles e.g., household, cosmetics. Includes spray tops, bottle tops and handles.			x			
	Food service disposables	Straws, stirrers	x			x		x
		On-premise food service disposables		x				x
		Off-premise plastic cups			x		x	
		Off-premise lids			x		x	
		Off-premise containers and clamshells			x	x		x
		Off-premise cutlery	x			x		x
	Pots, tubs and trays	Fresh fruit/vegetable tray/pot/punnet/tub	x	x	x	x		
		Pots/tubs for liquids and creams: yogurt, butter, spreads, chocolate/sweets, cream, chilled pot desserts and ice cream pots/tubs.			x		x	
		Meat tray		x			x	
		Ready meals trays, instant pot snacks			x	x	x	
		Other					x	
	B2B packaging	Pallets, crates, Intermediate Bulk Containers (IBCs), drums and barrels and expanded polystyrene. Includes secondary and tertiary packaging.	x		x			
	Household goods	Cosmetics, toys, buckets, bowls, flip flops, small household objects, etc.	x					

Plastic Category	**Product application**	**Product sub-category**	**Eliminate**	**Reuse**	**NDM**	**Paper**	**Coated paper**	**Compostable**
	Other rigid monomaterial packaging	Consumer goods' EPS packaging, plastic egg boxes, blister packs, clothes hangers, caps and lids	x			x		x
Flexible Monomat-erial	Carrier bags	N/A	x	x		x		x
	Films	Pouches, trash bags, wraps, 6-rings, netting and other flexibles	x		x	x	x	x
	B2B films	B2B shipping sacks, strapping, flexible intermediate bulk containers, bulk liners and rolls	x		x			x
Multimaterial/multilayer	Sachets and multilayer flexibles	Sachets	x		x	x	x	x
		Multilayer flexibles	x		x	x	x	x
	Laminated paper and aluminum	Plastic component of laminated aluminum (e.g., toothpaste and cosmetics tubes), and of carton, paper and aseptic cartons with >5% plastic coating, i.e., incompatible with paper recycling streams			x			x
	Household goods	Cosmetics, toys, pens, brooms, cigarette butts, small household objects, etc.	x					
	Diapers and hygiene products (plastic portion)	Sanitary items		x				x
		Wet-wipes		x		x		x
		Cotton bud sticks				x		
		Diapers		x	x			x

Table S21: Limiting factor scoring framework for reduction and substitution potential of a product application. TRL = technology readiness level. BAU = “Business as Usual’ scenario.

	Technology test	**Performance test**	**Convenience test**	**Affordability test**
Score	**Does a theoretical reduce (1st pass) or substitute (2nd pass) intervention exist?**	**Does the intervention satisfy performance and health requirements?**	**Is the intervention acceptable for lifestyle and convenience?**	**Are the cost implications of the alternative acceptable?**
4	Yes: TRL 9, available in multiple locations	Yes: meets the minimum performance requirements for sustained utility	Yes: near or better than BAU	Yes: net savings to society, or broadly acceptable to consumers
3	Only at pilot: TRL 5-8	Mostly: does not meet performance requirements for certain applications	Mostly: consumers or supply chains would face challenges	Mostly: unacceptable in some consumer segments or products
2	Only in labs: TRL 1-4	Partially: limited applications only	Partially: eco-conscious consumer only	Partially: eco-conscious consumers only
1	No alternative available	Unacceptable health or performance risk	Unacceptable lifestyle change	Unacceptable cost increase

Table S22: Limiting factor scores for 15 product applications in the six reduce and substitute levers (Table S19) by income level. Limiting factors (LF) were scored based on Table S21 on a scale of 1-4. A score of 4 indicates high feasibility and 1 indicating "not applicable." Archetype income levels: HI=high income, UMI=upper middle income, LMI=lower middle income and LI=lower income. NDM=new delivery models. NDM = new delivery model. B2B = business to business.

Plastic Category	Product application	Product sub-category	HI						UMI/LMI/LI					
			Reduce			Substitute			Reduce			Substitute		
			Eliminate	Reuse	NDM	Paper	Coated paper	Compostable	Eliminate	Reuse	NDM	Paper	Coated paper	Compostable
Rigid monomaterial	Water bottles	Still water only, including bottle tops	1	4	4	1	1	1	1	3	3	1	1	1
	Other food-grade bottles	Target market for refill (milk, soda, sparkling water)	1	1	3	1	1	1	1	1	3	1	1	1
		Remainder (juice, concentrates, sports drinks, etc.)	1	1	1	1	1	1	1	1	1	1	1	1
	Non-food-grade bottles	Non-food bottles e.g., household, cosmetics. Includes spraytops, bottle tops and handles	1	1	3	1	1	1	1	1	3	1	1	1
	Food service disposables	Straws, stirrers	3	1	1	4	1	2	3	1	1	3	1	2
		On-premise food service disposables	1	4	1	1	1	4	1	4	1	1	1	3
		Off-premise plastic cups	1	1	3	1	3	1	1	1	3	1	2	1
		Off-premise lids	1	1	3	2	1	2	1	1	3	2	1	2
		Off-premise containers and clamshells	1	1	3	4	1	4	1	1	3	2	1	3
		Off-premise cutlery	2	1	1	4	1	4	2	1	1	3	1	3
	Pots, tubs and trays	Fresh fruit/vegetables tray/pot/punnet/tub	3	2	3	4	1	1	3	2	3	3	1	1
		Pots/tubs for liquids and creams: Yogurt, butter, spreads, chocolate/sweets, cream, chilled pot desserts and ice cream pots/tubs.	1	1	2	1	2	1	1	1	2	1	2	1
		Meat tray	1	2	1	1	2	1	1	2	1	1	2	1
		Ready meals trays, instant pot snacks	1	1	2	3	2	1	1	1	2	2	2	1
		Other	1	1	1	1	2	1	1	1	1	1	2	1

Plastic Category	Product application	Product sub-category	HI						UMI/LMI/LI					
			Reduce			Substitute			Reduce			Substitute		
			Eliminate	Reuse	NDM	Paper	Coated paper	Compostable	Eliminate	Reuse	NDM	Paper	Coated paper	Compostable
Rigid monomaterial	B2B packaging	Pallets, crates, Intermediate Bulk Containers (IBCs), drums and barrels, expanded polystyrene. Includes secondary and tertiary packaging.	1	1	4	1	1	1	1	1	4	1	1	1
	Household goods	Cosmetics, toys, buckets, bowls, flip flops, small household objects, etc.	2	1	1	1	1	1	2	1	1	1	1	1
	Other rigid monomaterial packaging	Consumer goods' expanded polystyrene packaging, plastic egg boxes, blister packs, clothes hangers, caps and lids.	2	1	1	3	1	2	2	1	1	2	1	2
Flexible monomaterial	Carrier bags	N/A	3	4	1	3	1	4	2	4	1	2	1	4
	Films	Pouches, trash bags, wraps, 6-rings, netting and other flexibles.	2	1	2	2	3	3	2	1	2	2	2	3
	B2B films	B2B shipping sacks, strapping, FIBCs, bulk liners. rolls.	3	1	3	1	1	2	2	1	3	1	1	2
Multimaterial/multilayer	Sachets and multilayer flexibles	Sachets	2	1	3	2	3	2	1	1	3	2	2	2
		Multilayer flexibles	2	1	2	2	3	2	2	1	2	2	2	2
	Laminated paper and aluminum	Plastic component of laminated aluminum; carton, paper and aseptic cartons with >5% plastic coating.	1	1	2	1	1	3	1	1	2	1	1	2
	Household goods	Cosmetics, toys, pens, brooms, cigarette butts, small household objects, etc.	2	1	1	1	1	1	2	1	1	1	1	1
	Diapers and hygiene	Sanitary items	1	2	1	1	1	2	1	2	1	1	1	2
		Wet-wipes	1	3	1	4	1	2	1	3	1	2	1	2
		Cotton bud sticks	1	1	1	4	1	1	1	1	1	3	1	1
		Diapers	1	2	2	1	1	2	1	2	2	1	1	2

Table S23: Allocation of substituted plastic mass among the three substitute materials – paper, coated paper, compostables – based on limiting factor (LF) scores (Table S22). The % allocation is respective to the scores received.

Condition	LF scores for each material	% Plastic mass allocation
All three substitute materials are available	Identical LF scores for all three (2, 3 or 4)	33 to each
	LF scores of 4/4/3	45/45/10
	LF scores of 4/3/3	
	LF scores of 3/3/2	67/17/17
	LF scores of 3/2/2	
Two substitute materials are available	Identical LF scores for both (2, 3 or 4)	50/50
	LF scores of 4/3	75/25
	LF scores of 4/2	95/5
	LF scores of 3/2	90/10
One substitute material is available	Any score from 2-4	100

Table S24: Overall limiting factor level per product application and market penetration (level 4 represents the most feasible).

Level	2030 % of serviceable market reached	2040 % of serviceable market reached
4	50%	80%
3	20%	50%
2	1%	10%
1	0%	0%

Table S25: Proportion of product application attributed as multi-use packaging.

Product application	% of multi-use packaging that is plastic	Rationale
Water bottles	0%	Food contact
Other food-grade bottles	0%	Food contact
Non-food-grade bottles	100%	Non-food contact
Food service disposables	0%	Food contact
Pots, tubs and trays	0%	Food contact
B2B packaging [rigid monomaterial]	100%	Non-food contact
Carrier bags	100%	Non-food contact
Films [monomaterial]	33%	Partial food contact
B2B films [monomaterial]	100%	Non-food contact
Sachets and multilayer flexibles	33%	Partial food contact
Laminated paper and aluminum	0%	Food contact
Diapers and hygiene (plastic portion)	0%	No multi-use plastic solution available

Table S26: Baseline conditions used in scenario construction of plastic waste collection rates ($\%CR_{P}$;) by archetype for base year 2016 (30)**.**

Archetype	**Base Year (2016)**
HI-U	99%
HI-R	96%
UMI-U	85%
UMI-R	45%
LMI-U	71%
LMI-R	33%
LI-U	48%
LI-R	26%

Table S27: MFA 2040 targets used in scenario construction of assessed plastic waste collection rates (%CR_P, Arrow A1/Box B) by archetype.

Archetype	MFA for Collection rate for plastic waste
HI-U	100%
HI-R	100%
UMI-U	95%
UMI-R	50%
LMI-U	95%
LMI-R	50%
LI-U	95%
LI-R	50%

Table S28: Estimated proportion of waste pickers in 2016 based on Linzner and Lange (93) **for UMI and LMI archetypes and expert panel consensus on HI and LI archetypes.**

Income category	Urban population	Proportion of waste pickers in urban population	Number of waste pickers
HI	961,978,000	0.005%	48,099
UMI	1,693,419,000	0.33%	5,613,747
LMI	1,195,989,000	0.41%	4,922,319
LI	206,742,000	0.41%	850,886
Total	4,058,128,000		11,435,051

Table S29: Estimated total annual mass of plastic waste (recyclables) collected by waste pickers (Mt y^{-1}) in urban archetypes in 2016.

Urban archetypes by income category	Plastic collected in dumpsites (Arrow V1)	Plastic collected on streets (Arrow B2)	Total plastic collected (Box D)
HI	0.0	0.1	0.1
UMI	3.8	9.0	12.9
LMI	6.9	5.4	12.3
LI	1.2	0.9	2.1

Table S30: Estimated annual mass of plastic waste collected per waste picker in urban archetypes (t y^{-1}).

Urban archetypes by income category	Plastic collected in dumpsites (Arrow V1)	Plastic collected on streets (Arrow B2)	Total plastic collected (Box D)
HI	0.0	2.1	2.1
UMI	2.9	2.1	2.3
LMI	2.9	2.1	2.5
LI	2.9	2.1	2.5

Table S31: Proportion of plastic types (% wt. ar) collected by waste pickers in dumpsites and in streets, proportions remain static from 2016-2040.

Location of waste picker activities	**Rigid monomaterials (% wt. ar)**	**Flexible monomaterials (% wt. ar)**	**Multimaterials (% wt. ar)**
Streets (mean) (105, 106)	86%	14%	0%
Dumpsites (arithmetic mean of three sources (107–109))*	15%	82%	2%

*As data were not reported according to the same categories used in this analysis, they were normalized to the same approximate basis/denominator.

Table S32: Historical (2010-2015) mass of plastic waste generation ($m_{P,G}$ t.y^{-1}) and plastic waste collected for recycling for municipal solid waste (MSW). Mass ($m_{P,CfR}$ t.y^{-1}) and rate (%CfR wt. ar) are based on reported plastic waste generation mass ($m_{P,G}$ t.y^{-1}) and plastic waste recycled mass ($m_{P,CfR}$ t.y^{-1}) adjusted for losses and, in the case of the EU28, extrapolated from reported plastic packaging waste generation mass ($m_{P:PP,G}$ t.y^{-1}) and recycled mass ($m_{P:PP,R}$ t.y^{-1}) and estimated 2016 values (76, 113, 190).

Country	Basis	Metric	2010	2011	2012	2013	2014	2015	Historical CAGR	2016
US	**MSW**	Generated	31,400,000	32,100,000	32,070,000	32,750,000	33,390,000	34,500,000	1.90%	35,155,800
		Recycled	2,500,000	2,660,000	2,790,000	3,010,000	3,190,000	3,140,000	4.66%	3,286,454
		Recycling rate	7.96%	8.29%	8.70%	9.19%	9.55%	9.10%	2.71%	9.35%
Japan	**MSW (adjusted)**	Generated	4,590,000	4,650,000	4,460,000	4,540,000	4,420,000	4,350,000	-1.07%	4,303,527
		Recycled	931,507	958,904	931,507	931,507	890,411	917,808	-0.30%	915,093
		Recycling rate	20.29%	20.62%	20.89%	20.52%	20.15%	21.10%	0.78%	21.26%
EU28	**Extrapolated for MSW**	Generated	26,889,898	27,181,746	27,374,025	27,199,110	27,925,634	28,870,899	1.43%	29,549,159
		Recycled	6,715,061	7,011,874	7,295,915	7,601,657	8,293,913	8,742,302	5.42%	9,215,968
		Recycling rate	24.97%	25.80%	26.65%	27.95%	29.70%	30.28%	3.93%	31.47%
Total	**Partly extrapolated for MSW**	Generated	62,879,898	63,931,746	63,904,025	64,489,110	65,735,634	67,720,899	1.49%	68,732,935
		Recycled	10,146,568	10,630,778	11,017,422	11,543,164	12,374,324	12,800,110	4.76%	13,408,883
		Recycling rate	16.14%	16.63%	17.24%	17.90%	18.82%	18.90%	3.21%	19.51%

Table S33: Projected mass of waste plastic generated ($m_{P,G}$) and collected for recycling ($m_{P,CfR}$) based on individual adjustment of historical compounded annual growth rates (CAGR) of -50% for Japan, US and Europe for municipal solid waste (MSW).

Country	Basis	Metric	2016	2030	2040	Calculated CAGR
US	MSW	Generated	35,155,800	40,133,930	44,115,746	0.95%
		Recycled	3,286,454	4,538,291	5,714,918	2.33%
		Recycling rate	9.35%	11.29%	12.92%	1.36%
Japan	MSW (adjusted)	Generated	4,303,527	3,992,634	3,784,414	-0.53%
		Recycled	915,093	896,322	883,150	-0.15%
		Recycling rate	21.26%	22.46%	23.35%	0.39%
EU28	Extrapolated for MSW	Generated	29,549,159	32,652,643	35,067,049	0.72%
		Recycled	9,215,968	13,398,703	17,504,502	2.71%
		Recycling rate	31.47%	41.33%	50.20%	1.97%
Total	Partly extrapolated for MSW	Generated	68,732,935	76,779,207	82,967,209	0.79%
		Recycled	13,408,883	18,833,316	24,102,571	2.47%
		Recycling rate	19.51%	24.53%	29.05%	1.67%

Table S34: Model assumptions for the percentage of rigid plastic collected for recycling from two archetypes under the baseline and current commitments scenarios.

Archetype	Scenario	System component		2025 (%)	2030 (%)	2040 (%)
HI-U	Baseline	Arrow C1	% Collected for Recycling	47%	52%	63%
	Current Commitments	Arrow C1	% Collected for Recycling	64%	68%	79%
UMI-U	Baseline	Arrow D1	% informal to closed loop	25%	25%	25%
	Current Commitments	Arrow D1	% informal to closed loop	53%	53%	53%

Table S35: MFA of the rates of the mass of rigid monomaterial and flexible monomaterial MSW plastic waste collected for recycling as a proportion of the mass of plastic waste collected by the formal sector (%$\mathrm{CfR}_{\mathrm{P,FO}}$), for each archetype, derived from expert panel consensus. MFA = maximum foreseen assessment.

Archetype	MFA %$\mathrm{CfR}_{\mathrm{rigids,FO}}$	MFA %$\mathrm{CfR}_{\mathrm{flex,FO}}$
HI-U	87%	41%
HI-R	87%	41%
UMI-U	50%	20%
UMI-R	20%	0%
LMI-U	50%	20%
LMI-R	20%	0%
LI-U	0%	0%
LI-R	0%	0%

Table S36: Estimates for outcome of formal and informal sorting process for rigid monomaterial plastics (as % of plastic waste entering sorting).

	2016			2040 – After Intervention		
Income Group	**Going to Closed Loop**	**Going to Open Loop**	**Lost in sorting process**	**Going to Closed Loop**	**Going to Open Loop**	**Lost in sorting process**
Formal: (arrows F1, F2 and F3)						
HI	53%	27%	20%	65%	25%	10%
UMI	10%	70%	20%	20%	70%	10%
LMI	5%	75%	20%	20%	70%	10%
LI	0%	80%	20%	0%	90%	10%
Informal: (arrows D1, D2 and D3)						
HI	70%	25%	5%	80%	15%	5%
UMI	25%	70%	5%	35%	60%	5%
LMI	25%	70%	5%	35%	60%	5%
LI	25%	70%	5%	35%	60%	5%

Table S37: Estimates for outcome of formal and informal sorting process for flexible monomaterial plastics (as % of plastic waste entering sorting).

	2016			2040 – After Intervention		
Formal: (arrows F1, F2 and F3)						
Income Group	**Going to Closed Loop**	**Going to Open Loop**	**Lost in sorting process**	**Going to Closed Loop**	**Going to Open Loop**	**Lost in sorting process**
HI	20%	60%	20%	30%	60%	10%
UMI	10%	70%	20%	20%	70%	10%
LMI	5%	75%	20%	20%	70%	10%
LI	0%	80%	20%	0%	90%	10%

	2016			2040 – After Intervention			
Informal: (arrows D1, D2 and D3)							
Income Group	**Going to Closed Loop**	**Going to Open Loop**	**Lost in sorting process**	**Going to Closed Loop**	**Going to Open Loop**	**Lost in sorting process**	**Going to Chemical conversion**
HI	10%	85%	5%	40%	55%	5%	0%
UMI	10%	85%	5%	20%	65%	5%	10%
LMI	10%	85%	5%	20%	65%	5%	10%
LI	10%	85%	5%	10%	85%	5%	0%

Table S38: Recycling and loss rate improvements modeled.

Process	**Arrow**	**Loss rate 2016**	**MFA in 2030**	**MFA in 2040**
Sorting loss from formal sector	Arrow F3	20%	15%	10%
Mechanical recycling loss	Arrows I2 and J1	27%	20%	15%

Table S39: Percentage of mass of plastic waste flowing to chemical conversion – plastic to plastic (P2P) and plastic to fuel (P2F) in 2016 and 2040.

	2016			**2040 – After Intervention**		
Income Group	**P2P**	**P2F**	**Losses**	**P2P**	**P2F**	**Losses**
HI	0%	73%	27%	45%	45%	10%
UMI	0%	73%	27%	45%	45%	10%
LMI	0%	73%	27%	45%	45%	10%

Table S40: Disposal rates (as % of managed waste) for 'Business as Usual Scenario'.

	2016		2040	
Income Group	**Engineered landfill**	**Incineration with energy recovery**	**Engineered landfill**	**Incineration with energy recovery**
HI[a,d]	65%	35%	30%	70%
UMI[b,d]	85%	15%	58%	42%
LMI[c,d]	100%	0%	100%	0%
LI[c,d]	100%	0%	100%	0%

Sources: a = World Bank, 2018a (30); b = Fernandez, 2018 (191), Hu et al., 2015 (192), Hu et al., 2018 (193), Chinese Statistical Service (194) and Ji et al., 2016 (195); c = Paulraj et al. (196); d = expert panel consensus.

Table S41: Estimated mass (wt. ar) of imported and exported plastic waste for each archetype income level, derived from United Nations Comtrade data (45).

Income Group	Exports 2018 (as reported)	Imports 2018 (as reported)	Imports 2018 (adjusted to balance with export data)	Net export to another archetype
HI	6,880,401	3,872,370	4,257,299	2,623,102
UMI	787,598	2,370,811	2,606,479	-1,818,881
LMI	356,133	1,056,584	1,161,613	-805,480
LI	8,280	6,387	7,022	1,258
Total	**8,032,413**	**7,306,152**	**8,032,413**	**0**

Table S42: Classification of waste disposed as either mismanaged and managed, based on categories reported in Kaza et al. 2018 (30), by archetype.

	Waste Treatment Type						
	Controlled landfill	**Incineration with energy recovery**	**Landfill unspecified**	**Open dump**	**Sanitary landfill gas system**	**Waterways marine**	**Unaccounted for**
HI	Managed	Managed	Managed	Mis-managed	Managed	Mismanaged	Mismanaged
UMI	Managed	Managed	Mis-managed	Mis-managed	Managed	Mismanaged	Mismanaged
LMI	Managed	Managed	Mis-managed	Mis-managed	Managed	Mismanaged	Mismanaged
LI	Managed	Managed	Mis-managed	Mis-managed	Managed	Mismanaged	Mismanaged

Table S43: Adjusted proportion of managed plastic waste (Arrow L1) reported by Kaza et al. (30)**, classified according to Table S1 and adjusted using Eq. 15 and Eq. 16.**

Archetype	**Managed plastic waste; 2016 (as % of disposal)**	**Managed plastic waste; 2040 (as % of disposal)**
HI-U	96%	96%
HI-R	94%	94%
UMI-U	53%	48%
UMI-R	28%	28%
LMI-U	4%	4%
LMI-R	2%	2%
LI-U	3%	3%
LI-R	2%	2%

Table S44: Proportion of managed waste ($m_{P,MAN}$) in 2040 under 'System Change' scenario.

Archetype	**Managed plastic waste; 2040 (as % of disposal)**
HI-U	100%
HI-R	100%
UMI-U	90%
UMI-R	75%
LMI-U	50%
LMI-R	50%
LI-U	50%
LI-R	50%

Table S45: Rate of open burning of collected and uncollected plastic waste based on the rate of open burning of collected and uncollected municipal solid waste.

Income category	Rate of open burning of collected plastic waste in dumpsites (%$OB_{P,DS}$)	Rate of open burning of uncollected waste in residential areas (%$OB_{P,RES}$)
HI	13%	13%
UMI, LMI, and LI	60%	60%

Table S46: Sources and pathways for plastic waste to enter the aquatic environment identified and defined following expert panel consensus.

Source	Primary pathway	Secondary pathway
Uncollected plastic waste ($m_{P,UNCOL}$; Box Q)	Diffuse terrestrial dumping ($m_{P,DTDUMP}$; Arrow Q2) includes plastic waste generated in households, institutions or businesses that has been dumped by people who have to manage their own waste in the absence of waste collection services; littered plastic waste that is discarded onto land close to the point of consumption; and plastic waste that has been discharged into the sewerage system.	While some waste that is dumped on land will become buried in surface soil, or ensnared by vegetation and objects on the surface of the land (Box T), some plastic waste will move across land or through the air, being impelled by wind or surface water (Arrow T1).
	Direct discard to water (Arrow Q3) includes waste that has been dumped deliberately directly into rivers or coastal waters by residents, businesses or institutions as a method of waste management.	
Post-collection mismanaged waste ($m_{P,MISMAN}$; Box R).	Dumpsites and unprotected landfills (Arrow R2) see Section 10.2 for more detail.	Much of the waste entering dumpsites or unprotected landfills will become buried, however a portion may escape from the surface during or after deposition or in some cases be eroded from the margins through the action of wind or rain.
	Dumping into water by collection vehicles whose operators want to avoid tipping fees or travelling to a controlled disposal facility.	

Table S47: Transfer ratios based on expert panel consensus.

Pathway	**Arrow number and expression**	**Denominator**	**Rigid**		**Flexible**		**Multi**	
			<1km	**>1 km**	**<1km**	**>1 km**	**<1km**	**>1 km**
Direct to waterbody (resident)	Arrow Q3 $m_{P,DDRES}$	Q: Uncollected	20%	0.1%	20%	0.1%	20%	0.1%
Leakage to waterbody from terrestrial dumping	Arrow T1 $m_{P,DTDUMP,TRAN}$	T: Diffuse terrestrial dumping	10%	3%	35%	8%	35%	8%
Direct to waterbody (collection vehicle)	Arrow R1 $m_{P,DDCOL}$	R: Post-collection mismanaged	5%	5%	5%	5%	5%	5%
Dumpsite / unsanitary landfill leakage to water	Arrow V3 $m_{P,DS,TRAN,AL}$	V: Dumpsite / unsanitary landfill	1%	0.5%	8%	3%	8%	3%
Dumpsite / unsanitary landfill leakage to land	Arrow V4 $m_{P,DS,TRAN,TL}$	V: Dumpsite / unsanitary landfill	1%	1.5%	8%	13%	8%	13%

Table S48: Allocation of km driven to urban and rural roads.

% km driven on urban roads	52%
% km driven on urban motorways	16%
% km driven on rural roads	24%
% km driven on rural motorways	8%

Table S49: Transmission factors for tire wear particles (TWP) distribution per archetype to soil, air and waterways.

Transmission factors per archetype		**System Map Arrow**	**HI**	**UMI**	**LMI**	**LI**
Soil and air	Urban roads	MTA1	41%	53%	53%	53%
	Rural roads	MTA1	74%	86%	86%	86%
	Motorways	MTA1	45%	79%	79%	79%
	Runways	MTB1	41%	53%	53%	53%
Waterways	Urban roads	MTA2	17%	35%	42%	44%
	Rural roads	MTA2	14%	14%	14%	14%
	Motorways	MTA2	21%	21%	21%	21%
	Runways	MTB2	17%	35%	42%	44%

Table S50: Transmission factors for tire wear particles (TWP) capture in combined sewage treatment and SuDS.

Transmission factors per archetype		System Map Arrow	HI	UMI	LMI	LI
Capture in combined sewage treatment	Urban roads	MTA3	30%	13%	5%	4%
	Rural roads	MTA3	0%	0%	0%	0%
	Motorways	MTA3	0%	0%	0%	0%
	Runways	MTB3	30%	13%	5%	4%
Captured in SuDS	Urban roads	MTA4	13%	0%	0%	0%
	Rural roads	MTA4	12%	0%	0%	0%
	Motorways	MTA4	34%	0%	0%	0%
	Runways	MTB4	13%	0%	0%	0%

Table S51: Transmission factors for tire wear particles (TWP) disposal.

Transmission factors per archetype		**System Map Arrow**	**HI**	**UMI**	**LMI**	**LI**
Disposal in SuDS/soils	Safely removed and managed in SuDS	MTH2	100%	0%	0%	0%
	Captured/disposed in roadside soils	MTH1	0%	100%	100%	100%
Disposal fate of captured TWP	Thermal treatment with energy recovery	MA1	19%	4%	0%	0%
	Engineered landfills	MA2	35%	20%	2%	1%
	dumpsites/unsanitary landfills	MA3	2%	26%	48%	49%
	Terrestrial dumping	MA4	43%	50%	50%	50%

Table S52: Pellet losses from transport, recycling and plastic handling under “Business as Usual’ (BAU).

Mass (t) and loss rates (%)	System Map Box/Arrow	HI	UMI	LMI	LI
Mass transported by sea	MNB	51,274,574	41,401,878	25,639,808	4,550,700
Loss rate	MNB1	0.002			
Mass recycled	MNC	11,352,022	9,985,197	9,006,715	1,331,982
Loss rate	MNC1	0.03			
Mass held by plastic producers	MNA	139,801,395	112,883,246	69,907,571	12,407,788
Mass held by intermediary facilities [a]	MNA	349,503,489	282,208,114	174,768,928	31,019,469
Mass held by processors	MNA	139,801,395	112,883,246	69,907,571	12,407,788
Loss rate to drains for all handlers	MNA1	0.03			

Note: Plastic production and recycling masses upon which pellet masses were based came from the macroplastics model.

[a] Values are the mass held by producers * 2.5 (average number of times pellets are handled between producers and processors (61)).

Table S53: Transmission factors for pellet disposal, capture and runoff.

Transmission factors per archetype	**System Map Box/Arrow**	**HI**	**UMI**	**LMI**	**LI**
Disposal in SuDS/soils	MNH	30%	18%	5%	5%
	MND3				
Captured by combined sewage treatment	MNF	37%	18%	5%	5%
	MND2				
Runoff to waterways	MNE	33%	64%	90%	90%
	MND1				

Table S54: Model assumptions for textile losses during use phase (Boxes MSB and MSC).

Model assumption	**HI**	**UMI**	**LMI**	**LI**
People per household	3.1	3.7	4.6	5.1
Wash cycles per household	203	185	185	
Loads per household wash	3.3	2.3	1.7	
Textiles hand washed	0%	0%	82%	100%
Textiles machine washed (household)	89%	61%	18%	0%
Textiles machine washed (commercial)	11%	39%	0%	0%
Loss per kg of textile machine washed	180			
Loss per kg of textile hand washed	50			

Table S55: Model assumptions for sewage treatment and capture of textile microplastic. See the accompanying Excel file (https://dx.doi.org/10.5281/zenodo.3929470) for details on underlying assumptions and data sources.

Model Assumption	**System Map Box/ Arrow**	**HI**	**UMI**	**LMI**	**LI**
Treatment					
Share of handwashing connected to sewage treatment	MSB2	86%	40%	12%	10%
Share of household and commercial machine washing connected to sewage treatment	MSC2				
Share of production connected to sewage treatment	MSA2				
Share of primary sewage treatment	MF, MD2	16%	2%	69%	100%
Share of secondary sewage treatment	MG, MD3	46%	96%	29%	0%
Share of tertiary sewage treatment	MH, MD4	38%	3%	3%	0%
Capture/Removal (Box MA)					
Capture rate (primary)	MF2	73%			
Capture rate (secondary)	MG2	94%			
Capture rate (tertiary)	MH2	98%			
Capture rate in production	MSE2	73%			

Table S56: Market share and concentration data used to model personal care product (PCP) pollution. Data for Europe were applied to all archetypes, taking into account market share.

Share of wash-off PCP	21%
Share of stay-on PCP	79%
Share of wash-off PCP that contains microplastic	10%
Share of stay-on PCP that contains microplastic	10%
Microplastic concentration in wash-off PCP	10%
Microplastic concentration in stay-on PCP	2%

Table S57: Intervention levers modeled for each of the four microplastics sources. NA = not applicable.

Microplastic Source	**Reduce**	**Substitute**	**Dispose**
Tire wear particles (TWP)	Demand-side reduction of km driven in vehicles. HI: Assume linear 50% reduction per capita annually by 2040. Other archetypes: Assume linear 20% reduction per capita annually by 2040. Demand-side reduction of flights 50% reduction per capita by 2040. Eco-driving courses, traffic management 6% reduction in TWP loss rate (197).	Substitute tire materials for durability and lower loss rate. Assume 50% of countries legislating new tires must have 36% (198) lower release rates than today by 2040 (resulting in a linear decline in TWP loss rate to 59 mg/km in 2040).	NA
Pellets	Implement best practices to minimize the risk of pellet spills at each stage along the plastic supply chain, including remedial measures to clean up and dispose of pellets where spills occur, e.g., regulation across the supply chain, Operation Clean Sweep enforcement, port policies, etc. Reduce today's loss rates by a conservative estimate of 70% by 2040, assuming a linear decline from 2020. Reduce plastic production and therefore material mass handled. 52% of reduced plastic production resulting from the "Reduce" and "Substitute" wedges.	NA	NA
Textiles	Decrease the loss rate of textiles by improving fabric construction and design. Use lower quartile of the current loss rate (https://dx.doi.org/10.5281/zenodo.3929470).	NA	Install in-line washing machine filters. 95% of countries legislate that new washing machines must have filters capturing 88.5%*(199) of microfibers; assume that 50% of consumers use

Microplastic Source	**Reduce**	**Substitute**	**Dispose**
			these correctly. Assume a linear decline from the median loss rate to the lower quartile point loss rate by 2040, starting in 2020. Mandate filtering factory effluent 95% of countries mandate that all factories must use on-site sewage treatment equivalent to secondary or tertiary treatment. Extend share of households connected to wastewater treatment. Each archetype meets the Sustainable Development Goals of halving the proportion of untreated sewage by 2030 (200).
Personal care products (PCP)	NA	Ban microbeads and substitute with other microplastic ingredients. Assume 95% of each archetype passes a ban on wash-off PCP microplastic by 2040 (annual linear decline starting in 2020). Assume a 30% reduction in stay-on PCP microplastics through 2040.	Extend share of households connected to wastewater treatment. Each archetype meets the Sustainable Development Goals of halving the proportion of untreated sewage by 2030 (200).

*****Proprietary data provided by Andrej Krzan, PlanetCare.

Table S58: Overview of cost calculations for reduction levers.

Lever	End-of-life (EOL) costs
Eliminate (Box 0.1)	$0, as no waste produced
Reuse – consumer (Box 0.2)	"Waste ratio (consumer)" (mass of re-usable material required to meet 1 t of single-use plastic utility, expressed as a percentage – see Table S59) multiplied by Cost per t of EOL processing per archetype
Reuse – New Delivery Models (NDM) (Box 0.3)	"Waste ratio (NDM)" (mass of plastic required in the NDM to meet 1 t of single-use plastic utility) multiplied by Cost per t of EOL processing per archetype

Table S59: Waste Ratio (consumer) assumptions and references.

<table>
<tr><th>Multi-use item</th><th>Multi-use item mass, grams (a)</th><th>Number of reuses of multi-use item (b)</th><th>Single-use item mass (c)</th><th>Mass of waste replaced by multi-use item (d=b*c)</th><th colspan="2">Waste ratio (a/d)</th><th>Weighting</th></tr>
<tr><td>Plastic carrier bag (201–203)</td><td>34.9</td><td>6 (based on number of multi-use and single-use bags sold in UK, 2018, compared to single-use bags in 2014 before a ban was implemented).</td><td>10.05</td><td>60.3</td><td colspan="2">58%</td><td>13.3</td></tr>
<tr><td>Diaper (204)</td><td>132</td><td>80 (based on 47.5 multi-use diapers vs 3796 single-use diapers required over 2.5 years).</td><td>38.6</td><td>3088</td><td colspan="2">4%</td><td>4.9</td></tr>
<tr><td rowspan="2">Food service disposables</td><td>Estimate 1 - (205)</td><td>100% switch from disposable crockery to reusables. Number of reuses not specified.</td><td>NA</td><td>NA</td><td>11%</td><td rowspan="2">Mean: 15%</td><td rowspan="2">7.5</td></tr>
<tr><td>Estimate 2 - (206)</td><td>25.3% of disposables switched to reusables decreased food service item waste by 20.5%. Therefore assumed % mass savings of reducing 100% of disposables is 81% (=20.5%/25.3%).</td><td>NA</td><td>NA</td><td>18%</td></tr>
</table>

Table S60: New delivery model (NDM) waste Ratio assumptions and references.

Case study	**Method and assumptions**	**Waste Ratio**
Replenish (207)	Published waste reduction figure of 90%.	10%
Algramo*	Based on 75% reduction in bottles required.	25%
Cupclub	Re-usable cup and lid weighing 71.33g (=49.3+22.03g), reused 132 times, compared to a single-use expanded polystyrene (EPS) cup weighing 6.4g (=3.2+3.2g).	8%
Swedish Return System	Based on reusing a crate 150 times weighing 1.63kg (208), compared to a single-use crate weighing 60% less (209).	2%
Refill bottle scheme†	Based on 16 reuses of a 91g 2L returnable bottle, compared to a single-use 2L PET bottle weighing 41g	14%

*Confidential sales data analysis provided by Algramo on the company’s sales of refill products (June-Sept 2018).

†Confidential data provided by expert interview with a brand running both refill and non-refill bottle schemes.

Table S61: Cost (USD) per metric ton (t) of plastic shifted to multi-use non-plastic items.

	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
Reuse - NDM, EOL	25	34	14	18	9	13	6	8

Table S62: End-of-life (EOL) calculation data and sources for cost of paper substitute, by archetype. See sources and notes for each labeled row A through P below table. All costs in 2018 USD.

Row		**HI-U**	**HI-R**	**UMI-U**	**UMI-R**	**LMI-U**	**LMI-R**	**LI-U**	**LI-R**
A	EOL collection: cost per metric ton (t) of plastic substituted by paper								
B	Paper collection rate	100%	100%	100%	100%	100%	100%	100%	100%
C	Collection cost per t	$145	$196	$75	$101	$53	$72	$35	$47
D	Collection cost per t of plastic substituted to paper	$218	$294	$113	$152	$80	$107	$53	$71
E	**EOL recycling: cost per t of plastic substituted by paper**								
F	Paper recycling rate	78%	78%	35%	35%	35%	35%	35%	35%
G	Recycling cost per t of paper	$957	$957	$852	$852	$852	$852	$852	$852
H	Recycling revenue per t of paper	$600	$600	$600	$600	$600	$600	$600	$600
I	Costs of recycling per t of plastic substituted by paper	$418	$418	$132	$132	$132	$132	$132	$132
J	**2016 EOL disposal: cost per t of plastic substituted by paper**								
K	Paper disposal rate	22%	22%	65%	65%	65%	65%	65%	65%
L	Share of managed waste to engineered landfill	65%	65%	84%	84%	100%	100%	100%	100%
M	Landfill cost	$30	$30	$30	$30	$20	$20	$20	$20
N	Share of managed waste to incineration with energy recovery	35%	35%	16%	16%	0%	0%	0%	0%
O	Incineration with energy recovery cost minus revenue	$46	$46	$15	$15	$12	$12	$12	$12
P	Sum of costs of disposal per ton of plastic utility substituted by paper	$12	$12	$27	$27	$20	$20	$20	$20

Table notes:

- EOL costs for paper or coated paper, per metric ton of plastic substituted to paper, equals D+I+P
- D = 1.5 * B * C.
- I = 1.5 * F * (G – H).
- P = 1.5 * K * (L * M + N * O).
- Row C source: urban cost per metric ton is from Kaza et al 2018 (30); for rural costs we have added 35% additional cost, reflecting the increased cost of transport and collection systems in that archetype (see methodology in Section 10).

- Row F: HI is based on USA paper packaging rate (210); LI/LMI/UMI is the average of two data points available for the region due to lack of data overall: 20% for Indonesia (211) and 50% for the Philippines (212).
- Rows G and H are from the Consumer Goods Forum (213).
- Row K = 100% - F.
- Rows L and N show the split between incineration with energy recovery and landfilling by archetype for plastics in our model under BAU.
- Rows M and O are the cost per metric ton of incineration with energy recovery and landfilling used for managed plastics in our model under BAU.

Table S63: End-of-life (EOL) calculation data and sources for cost of compostables, by archetype. See sources and notes for each labeled row A through P below table. All costs in 2018 USD.

Row	Definition	HI-U	HI-R	UMI-U	UMI-R	LMI-U	LMI-R	LI-U	LI-R
A	**2016 EOL collection: cost per metric ton (t) of plastic utility substituted by compostables**								
B	Compostables collection rate (see notes)	100%	100%	88%	88%	92%	92%	96%	96%
C	Collection cost per t of compostable material	$145	$196	$75	$101	$53	$72	$35	$47
D	Collection cost per t of plastic substituted to compostables	$195	$263	$89	$120	$65	$88	$45	$61
E	**2016 EOL composting: cost per t of plastic utility substituted by compostables**								
F	Composting rate	35%	35%	12%	12%	8%	8%	4%	4%
G	Composting cost per t of compostables	$67	$67	$20	$20	$20	$20	$20	$20
H	Composting cost per t of plastic substituted by compostables	$32	$32	$3	$3	$2	$2	$1	$1
I	**2016 EOL disposal: cost per t of plastic utility substituted by compostables**								
J	Compostables disposal rate	65%	65%	88%	88%	92%	92%	96%	96%
K	Share of managed waste to engineered landfill	65%	65%	84%	84%	100%	100%	100%	100%
L	Landfill cost	$30	$30	$30	$30	$20	$20	$20	$20
M	Share of managed waste to incineration with energy recovery	35%	35%	16%	16%	0%	0%	0%	0%
N	Incineration with energy recovery cost	$46	$46	$15	$15	$12	$12	$12	$12

	minus revenue								
O	Cost of disposal per t of compostables	$36	$36	$28	$28	$20	$20	$20	$20
P	Costs of disposal per t of plastic substituted by compostables	$31	$31	$33	$33	$25	$25	$26	$26

Table notes:

- EOL costs of compostables per metric ton of plastic substituted to compostables = D+H+P.
- D = 1.3 * B * C.
- H = 1.3 * F * G.
- P = 1.3 * J * (K*L+M*N).
- Row B: as per the key assumptions made, collection for management is assumed to be 100%. However, in the LI/LMI/UMI archetypes, the type of composting referred to in our model is for locally handled, decentralized composting that does not require collection and transport costs. Therefore, the collection rate in these archetypes is 100% minus the archetype's % composted.
- Row C source (same as Row C in Table S62 for paper): urban cost per metric ton is from Kaza et al. 2018 (62); for rural costs we added 35% additional cost, reflecting the increased cost of transport and collection systems in that archetype (methodology in Section 10).
- Row F sources: composting rate was calculated for each archetype using data from Kaza et al. 2018 (62), as a mean value of all countries in the archetype for which data was available (55 data points: 33 HI, 11 UMI, 8 LMI, 3 LI). To calculate the composting rate for organic waste for each country, the mass of waste composted was divided by the calculated total mass of food, wood and green waste arising.
- Row G sources: HI reflects the cost of processing organic waste in the UK (£55 average, between £49 for mixed food and green waste and £61 for food waste only (214)), excluding 10% profit, using an exchange rate of 0.740634 (215). It was assumed that as compostable packaging expands it would be done in a manner where compostable packaging is designed to be suitable for composting processes, and/or that composting processes would be changed; if compostable packaging requires additional retention time or sorting costs, this could increase costs (not modeled). Due to a lack of data and the nascent stage of the technology in UMI/LMI/LI, the USD 20/t cost for these archetypes was based on expert panel consensus. This was compared against official documents for India (pages 13-19 of (216)), which suggested approximately USD 12/t capex plus opex for a 5 t/day window composting unit; however, this low cost may not reflect the latest composting technologies and practices. We assumed USD 20/t to be conservative.
- J = 100% - F.

- Rows K and M show the split between incineration with energy recovery and landfilling by archetype for managed plastics in our model under BAU.
- Rows L and N are the cost per metric ton of incineration with energy recovery and landfilling used for managed plastics in our model under BAU.

Table S64: Cost of collection (2018 USD)

Income group	Average cost for all waste ($/t)[1]	Weighted average urban in (allocated for plastics) ($/t)			Weighted average rural in (allocated for plastics) ($/t)		
		Opex	**Capex**	**Total**	**Opex**	**Capex**	**Total**
HI	145	149	64	213	202	86	288
UMI	75	81	35	115	109	47	156
LMI	53	56	24	81	76	33	109
LI	35	38	16	54	51	22	73

[1] Non-allocated cost. Source: World Bank (30), mid estimate.

Table S65: Estimated formal sorting costs ($/t) in USD.

Income Group	Opex	Capex	Total
HI	156	52	208
UMI	117	39	156
LMI	88	29	117
LI	66	22	88

Source: (203, 206, 207, 106, 108).

Table S66: Closed and open loop mechanical recycling costs ($/t input) in USD.

	Opex		Capex	
Income Group	**Closed Loop**	**Open Loop**	**Closed Loop**	**Open Loop**
HI	569 (+/- 20%)	410 (+/-20%)	160 (+/-20%)	120 (+/-20%)
UMI	452 (+/-20%)	307 (+/-20%)	140 (+/-20%)	90 (+/-20%)
LMI	300 (+/-20%)	200 (+/-20%)	115 (+/-20%)	75 (+/-20%)
LI	300 (+/-20%)	200 (+/-20%)	115 (+/-20%)	75 (+/-20%)

Sources: Based on expert panel consensus; Deloitte, 2015 (119).

Table S67: Chemical recycling costs ($/t input) in USD by archetype.

Income Group	Opex ($/t input)		Capex ($/t input)	
	P2P	**P2F**	**P2P**	**P2F**
HI	246	246	101	101
UMI	172	172	77	77
LMI	158	158	77	77

Sources: Based on expert panel consensus per proprietary data shared by expert panel member Jill Boughton.

Table S68: Recyclate sale price (in USD) by archetype.

Income Group	Mechanical Recycling ($/t output)		Chemical Conversion ($/t output) [c]	
	Closed Loop [a, b]	Open Loop	P2P	P2F
HI	1218	810	648	637
UMI	1157	770	645	637
LMI	1096	729	645	637
LI	1096	729	645	637

Sources: a = PIE (219); b = Based on expert panel consensus per proprietary data shared by expert panel member Ed Kosior; c = Based on expert panel consensus per proprietary data shared by expert panel member Jill Boughton.

Table S69: Closed loop sale prices ($/t output) in USD by archetype.

Income Group	Closed Loop ($/t output)	
	2016	2040 – after intervention
HI	1218	1350
UMI	1157	1283
LMI	1096	1215
LI	1096	1215

Sources: 2040 price assumptions and rationale based on expert panel consensus per proprietary data shared by expert panel member Ed Kosior. These sales prices assume clean, sorted, post-losses ready-for-market flakes or pellet.

Rationale for 2040:

- Archetype HI:
    - Virgin price (~USD 1500/t) minus 10%
- Archetype UMI:
    - Virgin price minus 15% (computed as HI minus 5%)
- Archetypes LMI/LI:
    - Virgin price minus 20% (computed as HI minus 10%)

Table S70: Open loop sale prices ($/t output) in USD by archetype.

Income Group	Open Loop ($/t output)	
	2016	**2040**
HI	810	1000
UMI	770	950
LMI	729	900
LI	729	900

Sources: 2040 price assumptions and rationale are based on expert panel consensus per proprietary data provided by expert panel member Ed Kosior.

Rationale for 2040:

- Archetype HI:
    - Virgin price (~USD 1500/t) minus 33%
- Archetype UMI:
    - Virgin price minus 37% (computed as HI minus 5%)
- Archetypes LMI/LI:
    - Virgin price minus 40% (computed as HI minus 10%)

Table S71: Engineered landfill costs ($/t input) in USD by archetype.

Income Group	Opex ($/t input)	Capex ($/t input)
HI	7.5	22.5
UMI	7.5	22.5
LMI	5.0	15.0
LI	5.0	15.0

Source: Based on data from the World Bank (30), Eunomia (174) and expert panel consensus.

Rationale and assumptions:

- Opex calculated based on utilized cost/t of waste instead of tipping fees to account for variation and non-true cost nature of tipping fees.
- Total cost split between opex/capex at 25/75 (174).
- Costs vary between HI/UMI and LMI/LI mainly due to labor costs.
- Stringency of environmental standards assumed high across all archetypes (barriers, methane capture, etc.).

Table S72: Incineration with energy recovery costs ($/t input) in USD by archetype.

Income Group	Opex ($/t input)	Capex ($/t input)
HI	63	27
UMI	28	21
LMI	26	21
LI	26	21

Source: Based on expert panel consensus per proprietary data shared by expert panel member Jill Boughton.

Rationale and assumptions:

- We assumed that all incineration is with energy recovery.
- Gross opex is used (i.e., non-inclusive of electricity/heat generation income).
- Total capex approximately $84M/$110M for HI/UMI, LMI, LI; 200,000 t/year capacity; 20-year lifetime.
- Rationale for capex: using same quality equipment with high environmental standards across archetypes.

Table S73: Incineration with energy recovery sale prices ($/t input) in USD by archetype.

Income Group	Revenue ($/t input)
HI	44
UMI	34
LMI	35
LI	35

Source: Based on World Bank, 2018 (30) and on expert panel consensus per proprietary data shared by expert panel member Jill Boughton.

Table S74: Closed loop sale prices ($/t output) in USD by archetype. Based on assumption of clean, sorted, post-losses ready-for-market flakes or pellet.

Income Group	Closed Loop ($/t output)	
	2016	2040 – after intervention
HI	1218	1350
UMI	1157	1283
LMI	1096	1215
LI	1096	1215

Source: Based on expert panel consensus per proprietary data shared by expert panel member Ed Kosior.

Rationale for 2040:

- Archetype HI:
    - Virgin price (~USD 1500/t) minus 10%
- Archetype UMI:
    - Virgin price minus 15% (computed as HI minus 5%)
- Archetypes LMI/LI:
    - Virgin price minus 20% (computed as HI minus 10%)

Table S75: Open loop sale prices ($/t output) in USD by archetype.

Income Group	Open Loop ($/t output)	
	2016	**2040**
HI	810	1000
UMI	770	950
LMI	729	900
LI	729	900

Source: 2040 price assumptions and rationale based on expert panel consensus per proprietary data shared by expert panel member Ed Kosior.

Rationale for 2040:

- Archetype HI:
    - Virgin price (~USD 1500/t) minus 33%
- Archetype UMI:
    - Virgin price minus 37% (computed as HI minus 5%)
- Archetypes LMI/LI:
    - Virgin price minus 40% (computed as HI minus 10%)

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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.
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