Title: Global environmental plastics dispersal under OECD policy scenarios towards 2060

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Abstract:

Plastics occupy a central role in the global economy, yet cause significant damage to ecosystems and human health. Recent studies and OECD reports have provided comprehensive roadmaps to reduce the environmental impacts of plastics, based on coordinated global action to reduce plastic consumption and improve waste management and recycling. Leakage of mismanaged plastic waste to aquatic environments, including the ocean, is a key policy variable, yet not well constrained in plastics life cycle analysis. Here we use a coupled land-ocean-atmosphere box model to simulate global plastic and microplastic dispersal for different policy scenarios. We update the global plastic and microplastic budget for the year 2015. Based on a revised estimate of the total marine plastic pool of 263 Tg, we constrain land to sea transport of plastics at 14 Tg y^{-1} for the year 2015, implying 4 to 7 times larger leakage than OECD estimates. Model simulation of two 'global action' policy scenarios, attaining near-zero mismanaged waste and >50% recycling by 2060, show a peak in land to sea transport of total plastics of 23 Tg y^{-1} around 2045 and a decrease thereafter. Land to sea transfer of microplastic, however, remains high during the 21st century due to its continued supply from the fragmentation of legacy mismanaged waste on land. Consequently, exposure to small microplastic, <300 µm, in air, terrestrial runoff, marine waters and sediment is estimated to increase 3 to 6-fold by 2060, compared to 2019, and can only be curbed by including remediation of terrestrial mismanaged plastic waste in policy scenarios.

Introduction

Plastics occupy a central role in the global economy, yet cause significant damage to ecosystems and human health (*1*, *2*). From 1950 to 2023 humans have produced 10,000 teragrams (Tg, 10^{12} grams, millions of metric tons) of fossil-fuel based polymers, an amount growing at a rate of 3% per year (*3*). Life cycle analysis has kept track of the fate of produced plastic polymers, in terms of usage (30%), waste management by incineration (10%), recycling (5%), landfilling (35%), and mismanagement (20%) (*3*, *4*). Landfilled and mismanaged, dumped plastic waste slowly fragments to microplastic at a rate of about 3% per year (*5*), adding to the substantial (14%) fraction of primary microplastics in waste (*6*). Both large plastic debris and microplastics disperse (also called 'leaking') by continental runoff and wind to pollute natural terrestrial and marine ecosystems (*7*), and have been documented across all continents and seas, from mountain tops to ocean trenches (*8*, *9*). Understanding past and future fragmentation and dispersal of plastics and microplastics is critical to determine their health impact on wildlife and humans (*10*). Plastic debris entangle aquatic species, and during use, after disposal, and upon ingestion plastics release toxic additives that disrupt endocrine function and increase risk for disease or disorders (*2*). International efforts are underway to curb the impact of plastic pollution, and different environmental policy scenarios have been proposed to limit dispersal (*4*, *6*).

Integrated understanding of global plastics dispersal, however, has been challenging thus far, with efforts focused on either marine (*11*, *12*), or terrestrial environments, sometimes in interaction with the atmosphere (*13–15*), but rarely addressing coupled biogeochemical cycling of plastics in the Earth surface system (*16*). Recent studies on plastics and microplastics in the surface and deep ocean, in marine sediments and in the atmosphere have provided critical information on plastics cycling and dispersal. The amount of buoyant plastics at the ocean surface, around 2 Tg (*12*, *17*), is just the tip of the marine plastics iceberg, with potentially up to 80 Tg of microplastics suspended in the deep ocean (*16*), and between 120 and 250 Tg deposited in marine sediments (*16*, *18*, *19*). The organization for economic cooperation and development (OECD) estimate of MMPW dispersal to the marine environment is smaller, around 30 Tg (*4*), underlining the incomplete understanding of global environmental plastics leakage.

In its 2022 "Global Plastics Outlook: Policy Scenarios to 2060" report, the OECD outlined two environmental policy scenarios to reduce the environmental impacts of plastics: The Regional Action and Global Ambition. The Regional Action scenario is based on improved circularity of plastics and reduced plastic pollution (leakage) for OECD countries, but less ambitious for non-OECD countries. The Global Ambition scenario is based on rapidly improved circularity of plastics and reduced plastic leakage in all countries, including near-zero plastic pollution by 2060. In this study, we integrate recent observations on environmental plastics and microplastics in a global plastic cycling box model, and use the model to simulate environmental plastics levels in water, soil, sediment and air under the OECD business as usual (BAU), the Regional Action and Global Ambition scenarios. We also evaluate the independent 'system change scenario' (SCS) from Lau et al. (*6*) which, similar to Global Ambition proposes forceful, but realistic measures to reduce, substitute, recycle, and dispose of plastics.

Global plastics budget and cycle

Materials and Methods

GBM-Plastics v1.1 model basics

We update the GBM-Plastics v1.0 model (global box model for plastics, updated version 1.1) to simulate how plastic waste is dispersed through the terrestrial, marine, and atmospheric environments upon release or emission (*16*). Three broad size classes of plastic waste are included: macroplastic (P, >5mm), large microplastic (LMP, >0.3mm and <5mm) and small microplastic (SMP, <0.3mm). The cut-off between SMP and LMP corresponds approximately to the neuston net mesh size for sampling aquatic microplastic, and to the upper limit of airborne microplastic fragments. We also use MP to denote the sum of SMP and LMP, which is often reported in observational studies. P fragment to LMP, and LMP fragment to SMP at a rate of 3 ± 1% per year ((*5*, *11*, *12*, *16*), and only SMP become airborne, emitted and deposited from and to oceans and land. GBM-Plastics is a first order box model, meaning that a plastic flux, F, out of a reservoir is linearly proportional to the mass, M, of plastics in the reservoir, i.e. $F = k \times M$. The mass transfer (rate) coefficients, k, are derived for each flux from published observations and estimates of F and M for the period 2010-2023, or from observed degradation or deposition rates, or by fitting. The v1.0 model is described in detail elsewhere, including the 15 mass balance equations for the different reservoirs (*16*). In v1.0, we fitted only 3 out of 23 k values to illustrate how recent knowledge on F, M and k, up to 2021 included, could generate a coherent set of k's and a simulated global plastic budget for the year 2015 that agrees within a factor of 10 with observations. In v1.1, several estimates of F and M have improved (see below), and decided to fit 12 out of 26 k values in order to improve agreement between simulations and observations.

In GBM plastics v1.1, we expanded the following features and parameterizations: Uncertainty analysis is now improved with a full Monte Carlo approach for all main input parameters and forcings. Terrestrial discarded pools of P, LMP and SMP are now subdivided into landfilled and mismanaged plastic waste (MMPW) pools, each receiving 50% of discarded waste from 1950 to 2015, and variable fractions beyond 2015. We also integrated the substantial, 45 ± 14 %, open burning of MMPW (*4*, *6*). Plastics in sanitary landfills no longer leak to their surrounding environment, including oceans over the timescale considered in this study (1950-2060). Over longer timescales, erosion of landfills may have to be considered. We therefore reparametrized land to sea P, LMP and SMP dispersal from their respective terrestrial MMPW pools only.

Marine SMP emission budget update

New observational estimates have been published for marine emission of SMP and for both P and MP in the marine environment, leading to changes in k values: In 2022 we assimilated the unique marine SMP emission model estimate of 8.6 (range 0-22) Tg y^{-1} from Brahney et al.(*13*), who acknowledged the important uncertainty associated with that estimate. Studies since then indicated the possible overestimation of marine SMP emission, with new estimates ranging from 0.001, to 8.9 Tg y^{-1}, and median SMP emission of 0.11 Tg y^{-1} (IQR 0.08-2.3; Table 1). The large variability depends on the study approach (experimental, modeling), the upper SMP size range considered (*28*), and the surface ocean SMP and atmospheric SMP datasets used. In this study we adopt the median SMP marine emission flux of 0.11 Tg y^{-1} and complete it with a similar consensus estimate of land SMP emissions of 0.18 Tg y^{-1} (median, IQR 0.16-0.44, Table 1). We also adopt a new global atmospheric SMP burden of 0.0036 Tg (median, IQR 0.002-0.017, Table 1), that is based on 3 studies. This ensemble of SMP burdens and fluxes in the air-sea and air-land system is critical in generating a coherent set of mass transfer coefficients, k for SMP dispersion via atmospheric pathways.

Compared to the preliminary GBM-plastics model and cycle (*16*), the updated model vs 1.1 incorporates 76x lower marine SMP emission and deposition fluxes, associated with a large uncertainty. The simulated lower marine emissions of 0.11 Tg y^{-1} (IQR 0.08 – 2.32) lead to lower SMP deposition over oceans and land, which in turn decreases the 'remote land' SMP stock from 28 Tg previously, to 3.3 ± 1.5 Tg. This model estimate needs field-based observations of soil SMP content and/or SMP deposition over remote land areas globally for a closer comparison and model optimization. Note that the mass of SMP in the atmosphere, and in marine emission and deposition fluxes is dominated by the upper aerosol size range of 70 µm in the model study results (*15*) that we assimilated. The lower marine SMP emissions lead to approximate lifetimes of SMP in the surface ocean mixed layer, against emission, of 1.2 years. The lifetime of atmospheric SMP in the planetary boundary layer, against deposition, is 5 days.

Shelf sediment plastic budget update

We previously estimated the shelf sediment P pool from a review study by (*20*) that approximated mean sea floor P concentrations of 5 Mg km^{-2} (uncertainty not given). Multiplying by the continental shelf surface of 2.89 10^7 km^2 resulted in a shelf sediment P pool of 51 Tg (Table 2). We also estimated a shelf sediment MP pool of 65 Tg (1σ, 21 to 78Tg) from subtidal sediment MP concentrations of 100 MP kg^{-1} (*38*), and a deep sediment MP pool of 1.5 Tg from deep sediment MP concentrations of 0.72 MP g^{-1} (*39*)(see (*16*) for details). A recent review by Martin et al. compiled published microplastic and mesoplastic data in the 10 µm to 25 mm range to estimate a global marine sediment pool of 170 Tg (range 25 to 900 Tg) (*18*). A new review by Zhu et al. estimates the global marine sediment plastics (P+LMP+SMP) pool to be 7 Tg (range 3 to 11 Tg) from remote operated vehicle (ROV) studies, and 255 Tg (range 5 to 571 Tg) from bottom trawl studies. They also estimate that 46% of global marine sediment plastics are deposited to the shelf, <200 m, and 54% to deep environments. Based on these studies, we derive a best estimate marine sediment P pool of 110 Tg (median, IQR: 39 to 191 Tg) in predominantly shelf, slope and continental rise environments (Table 2). The total marine plastics (P+LMP+SMP) pools is estimated to be 263 Tg (IQR 96-404).

Land to sea plastic transport estimate

Estimates of terrestrial plastic inputs to the marine environment remain subject to large variability. Bottom-up estimates based on population and waste management statistics, or river plastics concentration and size observations range from 0.1 to 15 Tg y^{-1} (*40–43*). Top-down estimates, using marine plastic mass balance calculations or 3D marine model plastic inventories can also provide useful estimate of plastics input from land, ranging from 0.5 to 13 Tg y-1 (*12*, *16*, *44*), and our box model falls into this category. Top-down model estimates depend directly on the integrated mass of plastics that has accumulated in the marine environment, in sediments, surface and deep ocean waters and on coastlines, including beaches. The land to sea plastic flux is then adjusted so that integrated historical inputs reproduce the presently (2010-2023) observed mass of plastics in the marine system. Based on our revised marine sediment plastics budget of 263 Tg (Table 2), we adjust k values for land to ocean transfer of P, LMP and SMP, and simulate land to sea transfer fluxes of 6.7, 7.2 and 3.2 Tg y^{-1} respectively (totaling 17 Tg y^{-1}) for the year 2019. The direct plastics input of 0.24 T y^{-1} from fishing activities (*12*) is implicitly included in our land to sea P flux estimate.

Surface ocean P, LMP, SMP budget updates

Surface ocean buoyant P and LMP pools were previously estimated to be on the order of 0.23 and 0.04 Tg (*21*). Inclusion of larger plastic debris in the floating P inventory, and availability of more data has recently produced a 10x larger P estimate of ~2.3 Tg (*17*) and 1.9 Tg (*12*) (Table 2). In order to model a larger mean surface ocean P pool of 2.1 ± 0.3 Tg, we had to adjust and lower the main outgoing surface ocean P flux in the model, which is sedimentation to the shelf, setting k to 38 y^{-1}. Due to sampling protocols surface ocean P and LMP are typically based on neuston net trawling and therefore reflect floating plastics >300µm. Physical considerations indicate that surface ocean SMP are more rapidly mixed down into the ocean mixed layer (*33*, *37*), and are therefore sampled using in situ pumps, or CTD bottles. Table 3 summarizes surface mixed layer SMP observations, ranging from 1.5 to 676 µg m^{-3}, with a median value of 7.0 µg m^{-3} (IQR 3.0 to 33), which multiplied by the global ocean surface of 361,900,000 km^2 and mean global mixed layer depth of 50 m, yields a surface ocean SMP pool of 0.13 Tg (median, IQR 0.05 to 0.82).

Policy scenario details

OECD Baseline, Regional Ambition, and Global Ambition policy scenarios for plastics production and waste management from 2019 to 2060 were obtained from (*4*) and aligned with production and waste statistics for 1950 to 2015 by (*3*). We also simulate the system change scenario (SCS) from Lau et al. which proposes ambitious, but realistic measures to reduce, substitute, recycle, and dispose of plastics. The original SCS scenario provided projections until the year 2040, which we extend here to 2060 by linear extrapolation. SCS plastic production and waste disposal statistics for recent years (2016) are lower than those from (*3*) and (*4*). We therefore anchored (by normalization) the SCS plastic production and waste disposal fractions for the period 2015 – 2040 to the data for 1950 – 2015 by Geyer et al. (*45*), in order to maintain intercomparability with OECD scenarios. We acknowledge that our 'SCS-like' plastic production and waste disposal estimates deviate to some extent from the original (*46*) estimates, but the overall ambition of the SCS policy trends are preserved. Plastic production and waste management statistics for the four scenarios are summarized in SI-1 and include past and projected quantities of plastic waste that is incinerated, recycled, and discarded (landfilled and mismanaged). The model is then run from 1950 to 2100, with only the k transfer coefficients and plastics production and waste generation statistics as external forcing. From 2060 to 2100, the model forcings are held constant at the 2060 values. All model uncertainties reported in SI-1 are 1σ standard deviation, based on 1000 Monte Carlo iterations of model scenario runs. The GBM-Plastics-v1.1 model code is included in SI-2 as Python scripts, and is also available via https://github.com/AlkuinKoenig/GBM-Plastics_v1.1

Key properties of the 2015 global plastics dispersal budget and cycle are:

1. The substantial mass of plastics, 263 Tg (median, IQR 96 – 204) that has polluted the marine environment, representing 3% of the 8,100 Tg of plastics produced since the year 1950.
2. The large mass of MMPW in dumps and discarded on land (discounted for open burning of MMPW), which drives dispersion to air and oceans: 440 ± 130 Tg of P, 260 ± 53 Tg of LMP, 110 ± 35 Tg of SMP.
3. The large mass of plastics discarded to landfills, 1600 ± 220 Tg of P, 800 ± 100 Tg LMP and 340 ± 90 Tg SMP, where it is immobilized temporarily, but not on millennial timescales (*16*).
4. The large subsurface oceanic LMP and SMP (82 ± 27 Tg), and shelf sediment P and LMP (175 Tg, IQR 60 - 269) reservoirs, compared to beached P and LMP (1.8 ± 1.4 Tg), and compared to surface ocean plastics (2.1 ± 0.3 Tg).
5. The substantial land to sea inputs of P (5.6 ± 2.2 Tg y^{-1}), LMP (6.0 ± 1.9 Tg y^{-1}), and SMP (2.4 ± 0.9 Tg y^{-1}), totaling 13.9 ± 3.9 T y^{-1} in 2015, that are required to explain the 263 Tg of plastics that have accumulated in the marine environment since 1950.

OECD and SCS policy scenarios

Plastic production and waste management statistics for the four scenarios are summarized in Figure 1 and SI-1 and include past and projected quantities of plastic waste that is incinerated, recycled, and discarded (landfilled and mismanaged). The model is then run from 1950 to 2100, with production and waste statistics as external forcing. From 2060 to 2100, the model forcings are held constant at the 2060 values, in order to illustrate the long-term plastics cycling dynamics for the different scenarios. Simulation results for the three OECD and the SCS policy scenarios (SI-1) are summarized in Figures 2 and 3 for key metrics. Figure 2a-d illustrates the level of policy ambitiousness in terms of annual plastics production, reaching 1200 (BAU), 990 (Regional), 810 (Global) and 440 Tg y^{-1} (SCS) in 2060, compared to 400 Tg y^{-1} in 2015. We recall that total plastics production (a-d) is the sum of virgin production and recycling. Figure 3e-h shows waste management and end-of-life trajectories, projecting notably a phase-out of MMPW by 2060 for the Global and SCS scenarios. Recycling by 2060 is progressively more ambitious from BAU (18%) to Regional (39%), to Global (59%) and SCS (53%) scenarios, while incineration stays around 20% in the three OECD scenarios and 32% in SCS. Figures 3i-l track the large amounts of cumulative landfilled waste and terrestrial MMPW, showing that despite the stabilization (Regional) or even decrease (Global, SCS) in the total amount of mismanaged P waste, the quantities of mismanaged SMP waste keep increasing towards and beyond 2060 due to the continuous fragmentation of legacy P to LMP and LMP to SMP at a rate of 3% per year.

In the GBM-Plastics model, the increasing cumulative MMPW pools of P, LMP and SMP on land ‘drive’ the amount plastics that are mobilized by runoff to the marine environment (Figure 3 m-p). The land to sea P, LMP, and SMP summed fluxes towards 2060 therefore show a continuous increase for BAU (43 Tg y^{-1}) and Regional (30 Tg y^{-1}) scenarios, and stabilizing fluxes for Global (22 Tg y^{-1}) and SCS (18 Tg y^{-1}) scenarios. All of these land to sea plastics fluxes are larger than the 2015 model reference flux of 14 Tg y^{-1}. When we follow land to sea input of MMPW, we find that the cumulative amount of floating surface ocean macroplastic (Figures 3 q-t) closely tracks land to sea inputs (m-p), and therefore MMPW policy scenarios (Figures 3e-h). Beached macroplastic mass keeps growing towards 2060 in BAU and Regional scenarios, but stabilizes in Global and SCS scenarios due to declining land to sea transfer, and slow but continuous fragmentation of beached P to LMP and SMP. The total amount of marine plastics (P+LMP+SMP, Figure 3u-x) increases in all scenarios from 263 Tg in 2015 to 1500 Tg (BAU), 1300 Tg (Regional), 1200 Tg (Global) and 1200 Tg (SCS) in 2060. The primary reason for this continuous increase, despite new MMPW reaching zero in Global and SCS scenarios, is the large amount of accumulated legacy MMPW on land (Figure 3i-l), that continues to be mobilized by runoff to the oceans.

In Figure 3 we convert LMP and SMP mass inventories and fluxes to approximate concentrations in key human and wildlife MP exposure environments. Atmospheric boundary layer SMP concentrations of 23 ng m^{-3} in 2015 increase to 100 (BAU), 89 (Regional), 80 (Global) and 74 (SCS) ng m^{-3} by 2060. Indicative SMP concentrations in global river runoff (37288 km^3 y^{-1} (*22*)) are estimated at 0.06 mg L^{-1} in 2015 and increase to 0.28 (BAU), 0.24 (Regional), 0.21 (Global) and 0.19 (SCS) mg L^{-1} by 2060. SMP concentrations in coastal runoff draining densely populated urban-industrial-agricultural catchments are likely 1-2 orders of magnitude higher. Indicative surface ocean (upper 50m mixed layer) SMP concentrations are 6.2 ng L^{-1} in 2015 and increase to 27 (BAU), 24 (Regional), 21 (Global) and 19 (SCS) ng L^{-1} by 2060. Surface Ocean concentrations in oceanic gyres where plastics accumulate are likely much higher than these global distributed estimates. It is of interest to note that SMP concentrations are 10,000 times higher in continental runoff than in surface ocean waters, suggesting that microplastic exposure in terrestrial aquatic foodwebs is disproportionally larger. Finally, SMP concentrations in shelf and slope sediments, as entry point for benthic marine food webs, are 16 mg kg^{-1} in 2015 (on a dry weight basis, in sediments deposited between 1950 and 2015), and reach 140 (BAU), 130 (Regional), 130 (Global), 120 (SCS) mg kg^{-1} by 2060.

Beyond 2060 the simulations, with plastics production and waste management kept constant at the 2060 values, show important differences driven by MMPW generation and leakage. The BAU scenario leads to unacceptably high amounts and concentrations of plastics in all environments, mostly increasing beyond 2060 due to sustained MMPW generation (15% of total waste). The OECD Regional Action scenario stabilizes plastics concentrations in air and water after 2060 at levels that are three times the 2015 reference values (Figure 3). Because MMPW remains 5% of total waste production in 2060 in the OECD Regional scenario, leakage to the terrestrial, marine and atmospheric environment remains large. Very different simulation results are reached for OECD Global Action and for the SCS scenarios, where MMPW reaches ~0% by 2060. This leads to a slow decrease in all leakage pathways, well-illustrated by the peak in 2045 and subsequent decline in land to sea plastic transfer, surface ocean floating plastics mass (Figure 2) and water and air MP concentrations (Figure 3). Ecosystem recovery for LMP is lower than for P, because even if MMPW generation of P after 2060 reaches ~0%, legacy MMPW (for P) continues to fragment on land and produce new LMP. Recovery for SMP is slower than for LMP for the same reason, and in addition 6% of the mismanaged SMP pool is emitted to air, deposited to land and ocean, and re-emitted before eventually settling to the deep ocean and terminal marine sediment sinks. This leads to delayed SMP dispersion across all Earth surface pools well into the 21st century.

Plastic and microplastic leakage

The OECD, using its ENV-Linkages model, provides an analysis of the leakage of mismanaged P waste to terrestrial (13 Tg y^{-1}) and aquatic (6 Tg y^{-1}) environments for the year 2019. An additional 2.7 Tg y^{-1} of MP leakage is estimated, from diverse MMPW and in-use sources, but without explicit fate. Of the 6 Tg y^{-1} aquatic P leakage, 1.7 Tg y^{-1} is transported to oceans, where 30 Tg is estimated to have accumulated since 1950 (*4*). In our GBM-Plastics model, P and MP leakage and land to sea transfer is constrained top-down from the much larger, observed, marine P pool of 114 Tg (IQR 40 – 197) and MP pool of 149 Tg (IQR 56-207)(Table 2). Consequently, our aquatic land to sea P and total plastics transport fluxes of 6.1 Tg y^{-1} and 16 Tg y^{-1} for the year 2019 are significantly larger than the OECD estimate of 1.7 Tg y^{-1} for 2019. This has important implications for our perception of the magnitude and duration of plastic pollution and exposure associated with the various environmental policy scenarios. First, the increasing number of studies that estimate large amounts of plastics in the deep ocean and marine sediments, indicates that plastics and microplastics are 4 to 9 times more mobile than currently assumed. Second, this implies that current and future plastics concentrations, and therefore human exposure, is equally underestimated. Third, the timing of ecosystem recovery is critically dependent on reductions in MMPW generation in the policy scenarios.

Important similarities in ENV-Linkages vs GBM-Plastics models are seen in the relative projections for 2060, illustrated here for the BAU scenario. The OECD projects MMPW generation and leakage to terrestrial and aquatic environments to triple by 2060: land to sea P transport increases from 1.4 to 4.0 Tg y^{-1} and the marine P stock increases 5-fold from 30 to 145 Tg. In Figure 3 we project that under the BAU scenario, land to sea P transport also triples from 6.0 to 17.5 Tg y^{-1}, and the marine P stock increases 4-fold from 113 to 536 Tg. These similar relative increases in leakage in all models reflects the same underlying first-order mass transfer parameterizations: a 2-fold increase in legacy MMPW on land, leads to a 2-fold increase in leakage from that pool.

Policy needs

The OECD Global Action and Lau et al's System Change Scenario are ambitious, realistic environmental policy scenarios that aim at reducing the impact of plastic waste on our environment. Here we ask the question whether they are ambitious enough? In terms of key environmental exposure metrics (Figure 3), even under Global Action and SCS, the SMP concentrations in air, runoff, ocean water and shelf sediments in 2060 are only marginally lower than for BAU, and are overall 3x higher than in 2019. The payoff of ambitious policy to reach ~0% MMPW comes after 2060, because land to sea dispersal of plastics and emission of SMP depends proportionally on the amount of MMPW on land. Figures 2 and 3 show that OECD Global Action and SCS plastics burdens, fluxes and exposure decrease systematically after 2045 for P and LMP, and after 2075 for SMP, gradually reaching 2019 levels from 2100 onwards. If we want ecosystem recovery to be faster, then policy efforts must include active remediation of the terrestrial MMPW pool, transferring recovered plastics to sanitary landfills or incinerating them. We recall however, that ecosystem recovery also depends on the efficiency of sanitary landfills in retaining plastic and microplastic waste, without further dispersal to ground and surface waters, and to air. The landfill P, LMP and SMP stocks are large (Figure 1), and only minor leakage would offset efforts on MMPW policy. For example, it is estimated that globally there are 100,000 coastal landfills in low-lying areas that are frequently unlined, and at risk of erosion, dispersing plastics to the marine environment (*23*).

In summary, the OECD Global Action and Lau et al.'s System Change scenarios are realistic policy propositions to address the impacts of plastic waste. They have been designed to be practically and economically feasible, and their underlying decrease in virgin plastic production, by substitution and recycling actions, will also decrease global greenhouse gas emissions from the plastics life-cycle. We recommend that Global Action and SCS policy be expanded with remediation of legacy MMPW pools on land, and by consolidation and/or remediation of landfilled waste that is at risk of dispersal.

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Supplementary Materials:
Materials and Methods
Data SI-1
Python model code

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Table 1. Published marine and land SMP emission estimates, atmospheric SMP burden, reported as median and interquartile range (IQR) values.

Study	**Marine SMP emission**	**Method**	**Marine data**	**Atmo data**	**Upper SMP size emitted**	**Atmospheric SMP burden**	**Land SMP emission**
	Tg/y				µm	Tg	
Brahney et al., 2021 (*13*)	8.6 (0-22)	Modeling (CAM)	(*24*)	(*13*)	70	0.0036	0.18
Evangeliou et al., 2022 (*14*)	8.9±3.5	Modeling (Flexpart)	NA	(*13*)	250		0.69
Yang et al., 2022 (*25*)	0.00077 (0.00003-0.0015)	Experiments	(*24*)		70		
Fu et al., 2023 (*15*)	0.12 (0.035-0.44)	Modeling (GEOS-Chem)	(*26*)	(*27*)	70	0.00051	0.13
Shaw et al., 2023 (*28*)	0.10 (0.02-7.4)	Experiments	(*12*)		500		
Sonke et al. 2022 (*16*)		observations		(*8*, *29*)		0.031	
Median, IQR	**0.11 (0.08-2.32)**					**0.0036 (0.002-0.017)**	**0.18 (0.16-0.44)**

Table 2. Published marine microplastic (P), large microplastic (LMP) and small microplastic (SMP) global stock estimates, in Tg, as median and interquartile range (IQR, 25th and 75th percentiles) or mean ± standard deviation (sd). Some studies report the sum of LMP and SMP, indicated by MP here.

Study	**Beach**		**Surface ocean**			**Deep ocean**	**Deep sediment**	**Shelf sediment**	**Shelf sediment**	**Total marine**		
	P	MP	P	LMP	SMP	MP	MP	P	MP	MP	P	P+MP
Sonke et al., 2022 (*16*)	1.3	0.5	0.23	0.036	0.003	82	1.0	51	65	149	52	201
Martin et al., 2022 (*18*)								170				
Zhu et al., 2023 - ROV (*19*)								3.2				
Zhu et al., 2023 - Trawl (*19*)								255				
Kaandorp et al., 2023 (*12*)			1.9	0.051								
Eriksen et al., 2014 (*21*)				0.036								
Eriksen et al., 2023 (*17*)			2.3									
This study					0.13							
median/mean	**1.3**	**0.5**	**2.1**	**0.044**	**0.13**	**82**	**1.0**	**110**	**65**	**149**	**114**	**263**
sd			0.3	0.011		27						
IQR(25th)					0.05			39	21	56	40	96
IQR(75th)					0.82			191	78	207	197	404

Table 3. Published marine small microplastic (SMP, <300µm) concentrations in the mixed layer (50 m), and estimated global stock, in Tg, as median and interquartile range (IQR, 25th and 75th percentiles).

Study	**Basin**	**Depth, m**	**SMP, µg m^{-3}**	**SMP, Tg**
Pabortsava and Lampitt, 2020 (*30*)	N-S Atl	10-70m	676	
Zhao et al., 2022 (*31*)	S-Atl	10-60m	1.6	
Eo et al., 2021 (*32*)	Korean East Sea	15-58m	56	
Poulain et al., 2019 (*33*)	N-Atl	0-0.1m	42[a]	
Ross et al., 2021 (*34*)	AO	5-21m	4.4	
Kanhai et al., 2018 (*35*)	AO	8-100m	10	
Tekman et al., 2020 (*36*)	AO	1-3m	1.5	
Enders et al., 2015 (*37*)	N-Atl	3m	3.4	
median			**7.0**	**0.13**
IQR 25th			3.0	0.05
IQR 75th			33	0.82

[a] estimated from the original median, ellipsoid corrected, SMP concentrations of 2100 µg km^{-2}.

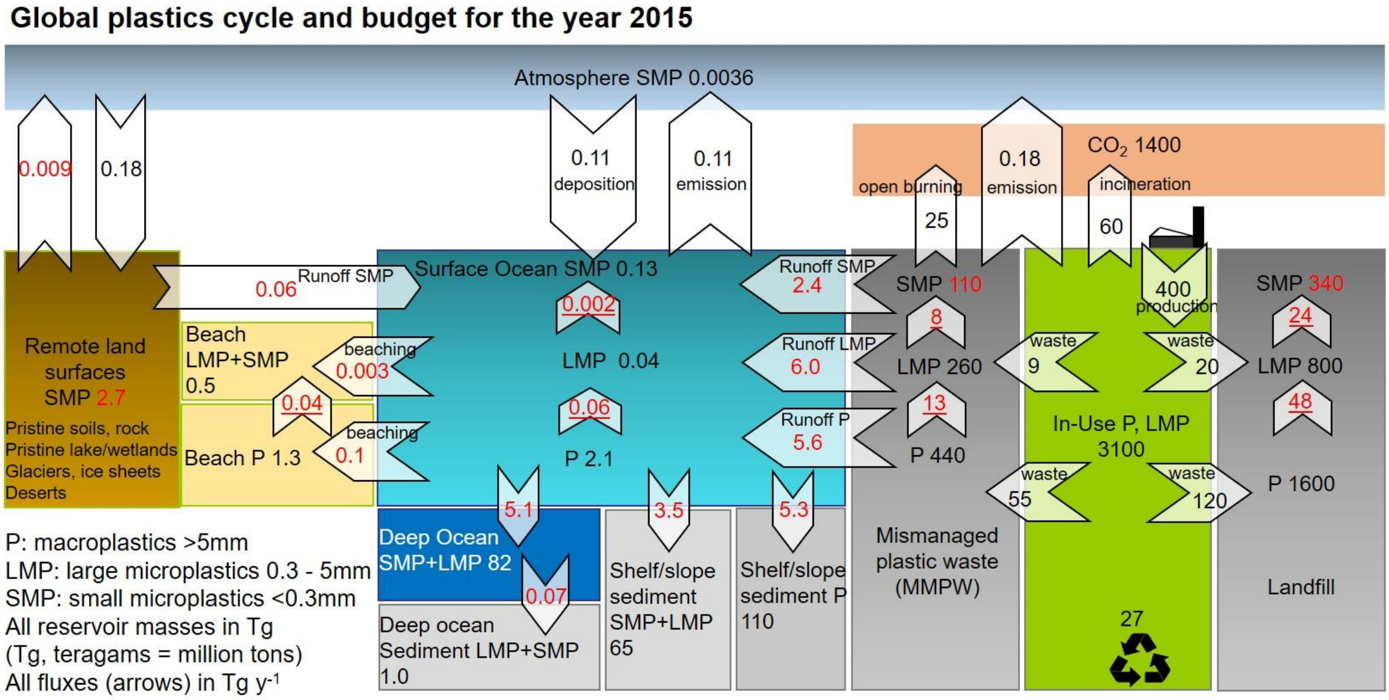

Figure 1. Global plastics budget and cycle for the year 2015. *Reservoir sizes are shown in teragrams (Tg), and fluxes in Tg y^{-1} (arrows). Three plastics size classes are considered: macroplastics > 5mm (P), microplastics from 0.3 to 5mm (LMP), and small microplastics <0.3mm (SMP) that can become airborne. Plastic waste is impounded in sanitary landfills, incinerated, or discarded as mismanaged plastic waste (MMPW), which is subject to open burning and to dispersal to the marine environment. The remote terrestrial reservoir is only impacted by airborne SMP deposition, re-emission and runoff. Numbers in black are based on production and waste statistics, and environmental P and MP observations (over the period 2006-2024), and numbers in red on the box model simulation. Underlined red fluxes indicate P and LMP degradation at a rate of 3% per year. Uncertainties are summarized in SI-1.*

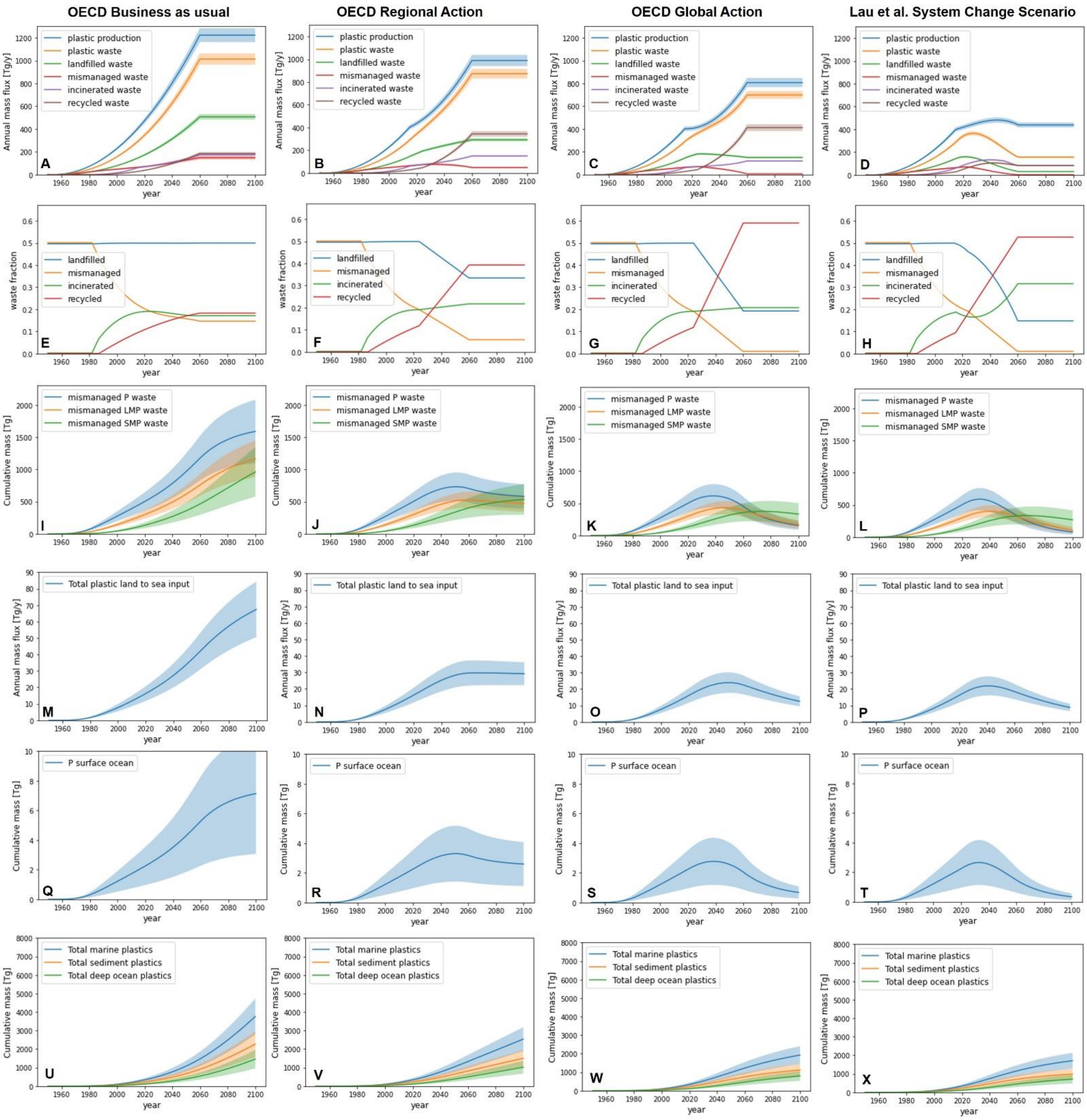

Figure 2 A-X. Model simulations of global plastics dispersal. *Four plastics production and waste management scenarios (columns) are simulated from 2016 to 2100: OECD business as usual (BAU), OECD Regional Action, OECD Global Action, and the System Change Scenario (SCS) from (*6*). From 1950 to 2015 all four scenarios use production and waste management statistics from (*3*). From 2060 to 2100 the statistics are fixed to the policy scenario endpoint values at 2060.*

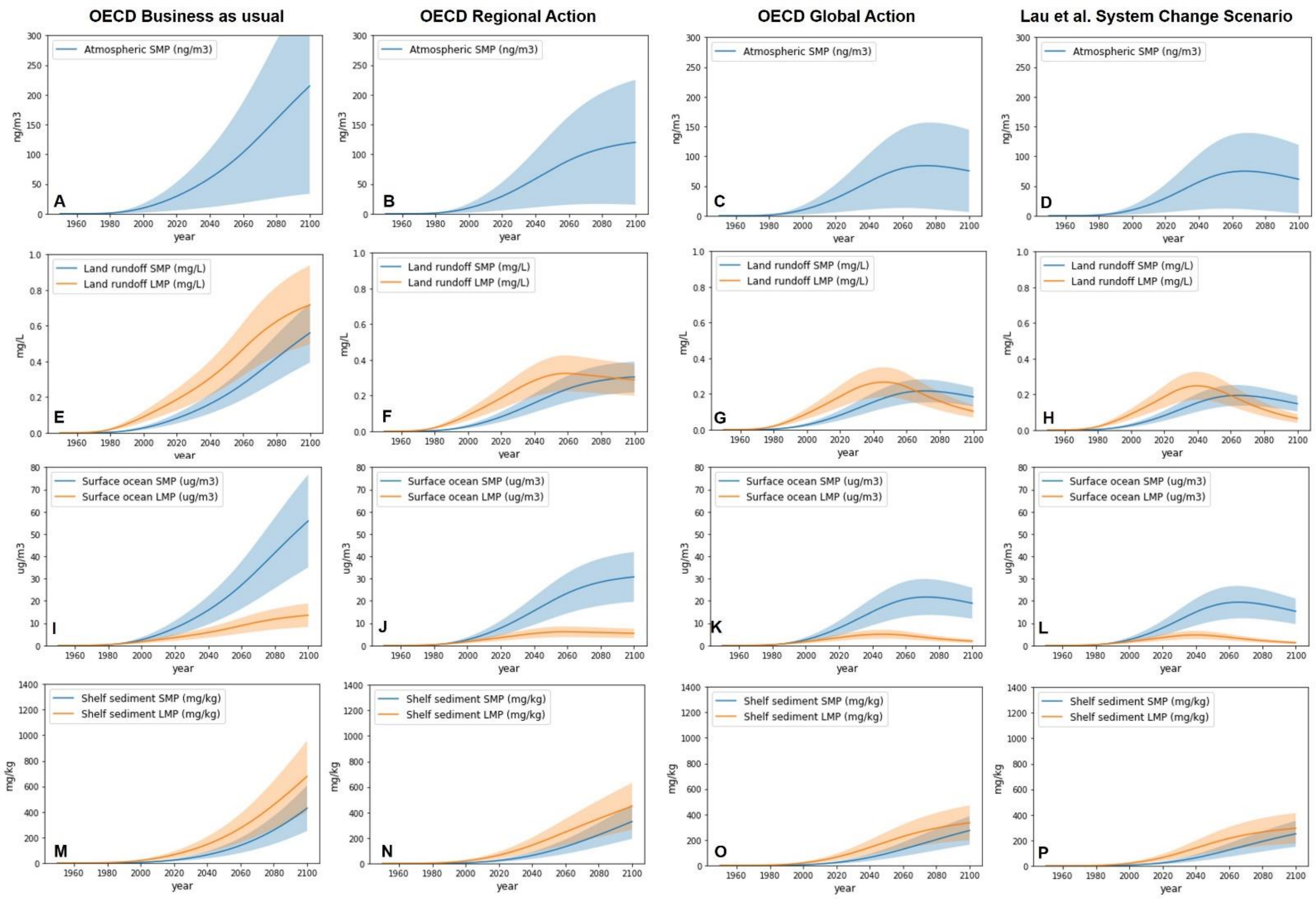

Figure 3 A-P. Model simulations of microplastic concentrations in air, water and sediment. *GBM-Plastics simulations of four plastics production and waste management scenarios (columns) from 2016 to 2100 are shown: OECD business as usual (BAU), OECD Regional Action, OECD Global Action, and the System Change Scenario (SCS) from (*6*).*