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Pathways to reduce global plastic waste mismanagement and greenhouse gas emissions by 2050

A. Samuel Pottinger[1,2]*†, Roland Geyer[3]*†, Nivedita Biyani [3,4]*†, Ciera C Martinez[1,2], Neil Nathan[4], Molly R Morse[4], Chao Liu[5], Shanying Hu[5], Magali de Bruyn[1,2], Carl Boettiger[1,2], Elijah Baker[4], Douglas J McCauley[1,2,4,6]*†

[1]Eric and Wendy Schmidt Center for Data Science and Environment, University of California Berkeley, Berkeley, CA, USA. [2]Department of Environmental Science, Policy & Management, University of California Berkeley, Berkeley, CA, USA. [3]Bren School of Environmental Science and Management, University of California Santa Barbara, Santa Barbara, CA, USA. [4]Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA, USA. [5]Department of Chemical Engineering, Tsinghua University, Beijing, China. [6]Ecology, Evolution, and Marine Biology Department, University of California Santa Barbara, Santa Barbara, CA, USA.

***Corresponding author. Email: sam.pottinger@berkeley.edu (A.S.P.); geyer@bren.ucsb.edu (R.G.); nrbiyani@ucsb.edu (N.B.); dmccauley@ucsb.edu (D.J.M.)**

†These authors contributed equally to this work.

Plastic production and plastic pollution negatively affect our environment, environmental justice, and climate change. Using detailed global and regional plastics datasets coupled with socio-economic data, we employ machine learning to predict that, without intervention, annual mismanaged plastic waste will nearly double to 121 Mt (100 - 139 Mt 95% CI) by 2050. Annual greenhouse gas emissions from the plastic system are projected to grow by 37% to 3.35 Gt CO_2 equivalent (3.09 - 3.54 CO_2e) over the same period. The United Nations plastic pollution treaty presents a unique opportunity to reshape these outcomes. We simulate eight candidate treaty policies and find that just four could together reduce mismanaged plastic waste by 91% (86% - 98%) and gross plastic-related greenhouse gas emissions by one third.

Plastic production has increased relentlessly since 1950, and alongside it plastic waste generation and mismanagement (*1*, *2*). In the environment, plastic waste breaks into ever smaller pieces, including micro- and nano-plastics (*3–5*), and thus negatively impacts myriad ecosystems (*6*), from the Arctic (*7*) to the deep ocean (*8*). Plastic pollution is associated with diverse human health impacts, such as elevated risk for cancers, cardiovascular disease, and reproductive health (*9–12*). The plastics system is also accelerating climate change, with emissions associated with the extraction and processing of oil and gas used to make plastic, plastic production, and plastic waste management (*13–15*). The disproportionate burden of plastic waste carried by the Global South, uneven plastic waste export practices, and patterns of situating plastic polymer facilities near vulnerable communities has created significant environmental justice issues (*16–18*).

Momentum has grown recently to preserve the constructive benefits of plastic while eliminating negative externalities (*19*). Perhaps most consequentially, in 2022, a resolution was adopted to begin developing an international legally binding United Nations treaty to curb plastic pollution (*20*). To contribute, we developed a model that utilizes machine learning to forecast trends in global production, use, and fate of all plastics to 2050 (*21*). We used the model to simulate the impact that eight policy interventions (*21*) may have, in isolation and when combined, upon global mismanaged plastic waste and plastic-associated greenhouse gas emissions: 1) recycled content mandate; 2) virgin plastic production cap; investment in 3) waste management infrastructure or 4) recycling infrastructure; 5) recycling rate mandate; 6) packaging tax; 7) reduction in single-use packaging; and 8) packaging reuse mandate. We provide open-source interactive software which allows for additional flexible exploration of candidate policy interventions (*21–23*). This work builds from and adds to important prior modeling efforts (*24–26*).

A machine learning approach to forecasting the future of plastics

A database for plastic production, consumption, and end-of-life (EOL) management was developed by extending and regionalizing data from existing sources (*21*, *27–29*). Production accounts for all virgin and recycled resins, fibers, and additives. We divided the world into four regions of major plastic production and consumption: North America (defined as the free trade partners: Canada, Mexico, and the United States), China, EU 30 (European Union plus UK, Switzerland, and Norway), and the remainder, referred to as Majority World. Apparent consumption in each region was derived from production data by accounting for trade of plastics or plastic-containing goods along the entire supply chain and is modeled by polymer type for eight economic sectors: packaging, construction, textiles, household/leisure/sport, electronics, transportation, agriculture, and other (*21*, *29*). Plastic waste generation was modeled by applying sector-specific product lifetime distributions (*26*). Plastic waste was labeled as mismanaged if it is not formally landfilled, incinerated, or recycled (*30*). Specific mismanagement routes and fates, such as littering, lack of formal collection, open dumping, or open burning (*24*, *31*), are not modeled.

We then developed and used a machine learning-based model within a Monte Carlo simulation using historic mass flow data and key socio-economic data (i.e., population and economic dynamics). This model propagates uncertainty and coordinates a number of random forest regressors to generate business as usual (BAU) projections to 2050 for future trends in plastic production, trade, and waste management (*21*). The model additionally estimates gross greenhouse gas (GHG) emissions associated with these different projections by using GHG intensities of plastic production, conversion, and waste fates (*13*). We note that actual emissions will be controlled by a diversity of industry and consumer decisions. However, these gross GHG estimates offer a useful view of the general magnitude and directionality of direct emissions.

In 2020, annual global plastic consumption reached 547 Mt, 86% of which was virgin and 14% recycled plastic. China was the largest consumer of plastics, accounting for 36% of the consumption; followed by Majority World 28%, EU 30 18%, and North America 18% (Fig. 1). Globally, plastic consumption was dominated by packaging (32%), followed by construction (17%) and textiles (16%). Significant differences in regional historic plastic use and socio-economic trends (Fig. S2) (*21*) cause future projections for plastic consumption to vary substantially by region. China's consumption is projected to peak around 2030 and decrease thereafter. Consumption in the EU 30 is expected to level off around 2025 before reverting to its 2020 baseline. In sharp contrast, total plastic consumption in North America and Majority World is predicted to grow. Without intervention, annual global consumption reaches 749 Mt in 2050 (695 - 789 Mt 95% CI), with an identical split between virgin and recycled plastic and similar sectoral breakdown (Fig. 2). This represents 37% growth in global plastic consumption over 30 years but is lower than the estimates of others; e.g., 976 Mt estimated by the OECD (*32*).

In 2020, North America and EU 30 consumed the highest amounts of plastic per capita (195 and 187 kg capita^{-1} yr^{-1}, respectively; Fig. 1), followed by China (138). Compared to North America and EU 30, Majority World consumed less than one sixth the amount of plastic per capita (29 kg capita^{-1} yr^{-1}). Per capita plastic consumption in Majority World was projected to only moderately increase to 34 kg capita^{-1} yr^{-1} (30 - 38) by 2050. China's per capita consumption grew the fastest during the last 20 years but is expected to level off at 158 kg capita^{-1} yr^{-1} (143 - 174) and revert to its 2020 value. Per capita consumption in the EU 30 is projected to similarly grow to 211 kg capita^{-1} yr^{-1} (201 - 221) before also reverting to its 2020 value. In stark contrast, North American per capita plastic consumption is expected to grow to 389 kg capita^{-1} yr^{-1} (352 - 416) by 2050 – an order of magnitude higher than Majority World.

In 2020 the world generated 425 Mt of plastic waste, 39% of which went to landfill, 24% to formal incineration, and 22% was recycled (Fig. 3). The remaining 15%, or 62 Mt, was mismanaged. Around 90% of mismanaged plastic waste occurred in Majority World, while China, North America, and EU 30 each generated only 3-4%. These findings are broadly consistent with previous studies of mismanaged plastic waste (*2*, *33*–*35*). Global annual plastic waste generation is set to grow by 62% to 687 Mt (639 - 734 Mt) in 2050 (Fig. 2). The expected changes in waste management vary significantly by region. However, when averaged globally, the expected landfilled and incinerated fractions remain unchanged, while the recycled fraction decreases (1 - 5%) and the mismanaged fraction increases by 3% (0 - 5%). The absolute amount of plastic recycling is expected to increase from 95 to 127 Mt (110 - 143 Mt), while the annual amount of mismanaged plastic waste is set to almost double to 121 Mt (100 - 139 Mt) in 2050 (Fig. 2, 3). 39 Mt (23 - 54 Mt) of that additional mismanaged waste is expected in Majority World and another 16 Mt (4 - 28 Mt) in China. In 2020, plastic production, conversion, and waste management generated an estimated 2.45 Gt CO_2 equivalent (CO_2e), or 5% of global industrial GHG emissions (*36*). This value is expected to increase to 3.35 Gt (3.09 - 3.54 Gt) CO_2e by 2050.

Testing the impact of global policy interventions

To explore how globally implemented policies could alter 2050 BAU projections, we simulated eight interventions currently being considered in the treaty draft (Fig. 4) (*21*, *37*). The dynamics of economic interventions (e.g., taxes, fees, or investment) are modeled based on existing data and literature such as observed decreases in consumption under taxation schemes, actual capital expenditures for infrastructure, and operating expenditures of different waste fates (Table S1). For physical interventions (e.g., bans, production caps, minimum collection rates), the mass flow changes are calculated mechanistically. Interactions between policies are managed through a constraints-based approach (*21*). While we selected a specific parameterization for these eight policies (*21*), we note that users can modify these assumptions in our web-based visualization software (*23*). Interventions can be investigated individually or can be toggled as dynamic collectives. Given that a central aim of the treaty is to eliminate mismanaged plastic waste (*38*), our model focuses on reducing the mass of mismanaged plastic waste, while also calculating gross GHG implications.

We recognize that there are many other important policies being considered for inclusion in the treaty. For example, we model some extended producer responsibility (EPR) policies (e.g., investments that could be generated from EPR fees;

recycling collection rate targets; recycling content targets; and reuse targets), but not all of them (e.g., variable fee targets; deposit refund systems (*39–41*)). Importantly, we also note that many candidate treaty actions cannot be tested in this particular analytical framework, yet could deliver essential advances in human health and environmental justice (*9*, *18*, *42*, *43*).

Of the eight policies we focused on, a global 40% minimum recycled content mandate across all sectors yields the single largest reduction of mismanaged plastic waste (Fig. 4). This intervention is expected to halve plastic mismanagement in 2050 from 121 Mt (101 - 139) in BAU to 59 Mt (46 - 72). Projected 2050 plastic consumption remains unchanged, but at least 40% of plastic used would come from secondary production. This would result in a reduction of anticipated 2050 GHG emissions from 3.35 (3.09 - 3.54) Gt in BAU to 2.79 (2.55 - 2.95) Gt CO_2e (Fig. 4).

Instituting a cap to global virgin plastic production (*21*, *37*, *44*) at 2020 levels yields the second largest individual reduction of mismanaged plastic waste, cutting plastic waste mismanagement in 2050 from 121 (101 - 139) to 72 (57 - 85) Mt. The cap results in both reduced consumption and increased recycling. Both responses not only reduce plastic waste mismanagement, but also lead to gross reductions in GHG emissions from plastic production, conversion, and disposal. A production cap at 2020 levels would drive 2050 GHG emissions from 3.35 (3.09 - 3.54) to 2.76 (2.55 - 2.91) Gt CO_2e, the largest gross reduction we observed.

Modeling a $50 billion total investment in waste management infrastructure (e.g., construction/expansion of sanitary landfills, increases in waste collection programs) yields similar reductions in mismanaged plastic waste. Funds for such an investment could be raised through EPR mechanisms, fees, or taxes. A global excise tax of one cent USD per kg of virgin plastic, for example, would raise in excess of $5 billion annually and is estimated to have little to no adverse economic or social impacts (*45*). A $50 billion investment is expected to reduce plastic waste mismanagement in 2050 from 121 (101 - 139) to 74 (53 - 93) Mt by increasing formal collection, incineration, and landfill. This investment is observed to have the largest impact when directed to Majority World nations. This intervention does not directly impact plastic production or consumption, but the reduction in mismanagement, and thus open burning of plastic waste (*31*), reduces 2050 GHG emissions from 3.35 (3.09 - 3.54) to 3.33 (3.08 - 3.52) Gt CO_2e.

A $100 billion investment in recycling infrastructure would lower mismanaged plastic waste in 2050 from 121 (101 - 139) to 91 (73 - 110) Mt by increasing formal collection and recycling. The effectiveness of this policy is dampened by an expected increase in total plastic production, consumption, and waste generation. Altogether, this investment slightly decreases 2050 GHG emissions from 3.35 (3.09 - 3.54) to 3.25 (2.99 - 3.46) Gt CO_2e.

Mandating a global 40% minimum rate of plastic waste collection for recycling results in a comparable reduction in 2050 plastic waste mismanagement of 30 (3 - 56) Mt, i.e., from 121 (101 - 139) to 91 (75 - 106) Mt. This rate is the ratio between the amount of waste collected for recycling and the amount of overall waste generation. It should not be confused with a recycling rate, which also accounts for the substantial yield loss from plastic recycling (*46*). Another reason for its diminished impact relative to the previously mentioned recycled content policy is that mandating collection for recycling increases total production and consumption since the resulting secondary material does not displace virgin production one-to-one (*47*). In the baseline scenario of this intervention, 2050 consumption increases from 749 (695 - 789) to 771 (712 - 818) Mt. 2050 GHG emissions decrease from 3.35 (3.09 - 3.54) to 3.28 (3.01 - 3.49) Gt CO_2e.

All aforementioned policy interventions apply to all eight plastic-consuming sectors (Fig. 2). The most impactful packaging sector-only policy intervention modeled is a packaging consumption tax (e.g., parameterized to approximate the behavior of taxes on plastic packaging used in regional contexts; Table S4) (*21*). With such a tax, 2050 consumption, and thus waste generation, of plastic packaging is reduced by 145 (112 - 162) Mt. Plastic waste mismanagement decreases from 121 (101 - 139) to 97 (76 - 114) Mt. Modeled GHG emissions experience the second largest reduction of all single-policy scenarios, from 3.35 (3.09 - 3.54) to 2.78 (2.65 - 3.10) Gt CO_2e.

The second packaging-only policy simulates a mandated reduction in single-use packaging (achieved via product bans or other measures (*21*)). This 45% reduction in overall plastic packaging cuts packaging consumption in 2050 by 98 (70 - 123) Mt. This reduces mismanaged plastic waste in 2050 from 121 (101 - 139) to 103 (85 -123) Mt and the modeled plastic-related 2050 GHG emissions from 3.35 (3.09 - 3.54) to 2.96 (2.73 - 3.17) Gt CO_2e.

The final packaging-only policy studied is a packaging reuse mandate (e.g., beverage bottles). An 80% reuse rate would lead to a reduction of plastic packaging by 74 (42 - 93) Mt at 2050, coinciding with a reduction in plastic waste mismanagement from 121 (101 - 139) to 109 (89 - 129) Mt, and GHG emissions drop from 3.35 (3.09 - 3.54) to 3.06 (2.84 - 3.30) Gt CO_2e.

While the mismanaged plastic waste reductions from the packaging-only policy interventions are smaller than the other cross-sectoral interventions, they are likely to have outsized environmental benefits since leakage of often lightweight plastic packaging into the environment is estimated to be particularly large (*48*, *49*).

As mentioned earlier, the modeling framework and online tool facilitate the flexible exploration of policy bundles – such as are being considered in the UN treaty. As one example, we consider a combination of four policies selected primarily to minimize mismanaged plastic waste: a virgin plastic production cap at 2020 levels, a high packaging consumption tax, a 40% minimum recycled content mandate, and a $50 billion investment in waste management. This policy bundle is projected to reduce plastic waste mismanagement in 2050 by 91% (86% - 98%), from 121 (101 - 139) to 11 (4 - 19) Mt (Fig. 4), and to reduce gross plastic-related 2050 GHG emission by one third, from 3.35 (3.09 - 3.54) to 2.09 (1.97 - 2.36) Gt CO_2e (Fig. 4).

Conclusion

These results suggest that it is possible to substantially reduce plastic waste mismanagement – one of the grand environmental challenges of the modern era (*50*). However, it is also sobering and instructive to consider the robustness of the policy package required to achieve such a result.

We acknowledge that there is uncertainty in our database, in addition to the modeling uncertainty that we attempt to quantify. Also, lacking robust regional landfill, recycling, and formal incineration rates at sector-level, we must assume that intraregional waste fate propensities are the same across all sectors. Measures under discussion in the UN treaty that would improve data disclosure and reporting could reduce these gaps. We also note that our model assumes successful implementation of policies. Should compliance be low, then higher ambition would be required to generate equivalent treaty impacts.

Even so, our BAU forecasts highlight just how large the mismanaged plastic waste problem will grow without intervention. Importantly, the burden of this unmitigated growth of plastic waste will be inequitably placed upon the world's least wealthy countries who consume the least amount of plastic per capita.

We observe great variation in the forecasted impact of different policies upon reducing mismanaged plastic waste. Minimum recycled content mandates, investments in waste management, caps to virgin production, and a packaging consumption tax all have outsized effects, both individually but especially in combination. The policy package we model that includes these four policies reduces waste mismanagement to very low levels (Fig. 4).

While we observe that reductions in GHG emissions are often a co-benefit of addressing mismanaged plastic waste with policies, it is noteworthy that reductions in these two currencies are not always fully aligned. Policies that reduce mismanaged plastic waste via upstream interventions (e.g., cap to virgin plastic production) yield the largest reductions in GHG emissions in our analysis (Fig. 4). Future work that includes additional impacts of mismanagement on climate change (e.g., microplastics impacts on the carbon pump) will further improve these estimates (*15*, *51*–*54*). While the aforementioned policies would deliver tangible climate benefits, they would be only minor contributions toward the Paris Agreement (i.e., the 1.25 Gt CO_2e reduced via our four policy bundle are less than 3% of current annual industrial GHG emissions) (*55*). Even with such reforms, plastic industry emissions would remain high.

Collectively, these observations provide timely insight into how to maximize the impact of the UN plastic pollution treaty both as it is being drafted and over the longer time horizon of its implementation. It is clear from these results that, with sufficient political will, there is enough technical potential to dramatically reduce mismanaged plastic waste and meaningfully address some of the more insidious associated issues. Finally, this effort also showcases a general methodological approach by which policies can be openly and flexibly tested via interactive simulation to guide and strengthen environmental decision-making in other important contexts.

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SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adr3837
Materials and Methods
Supplementary Text
Figures S1 to S4
Tables S1 to S6
References (*56*–*77*)

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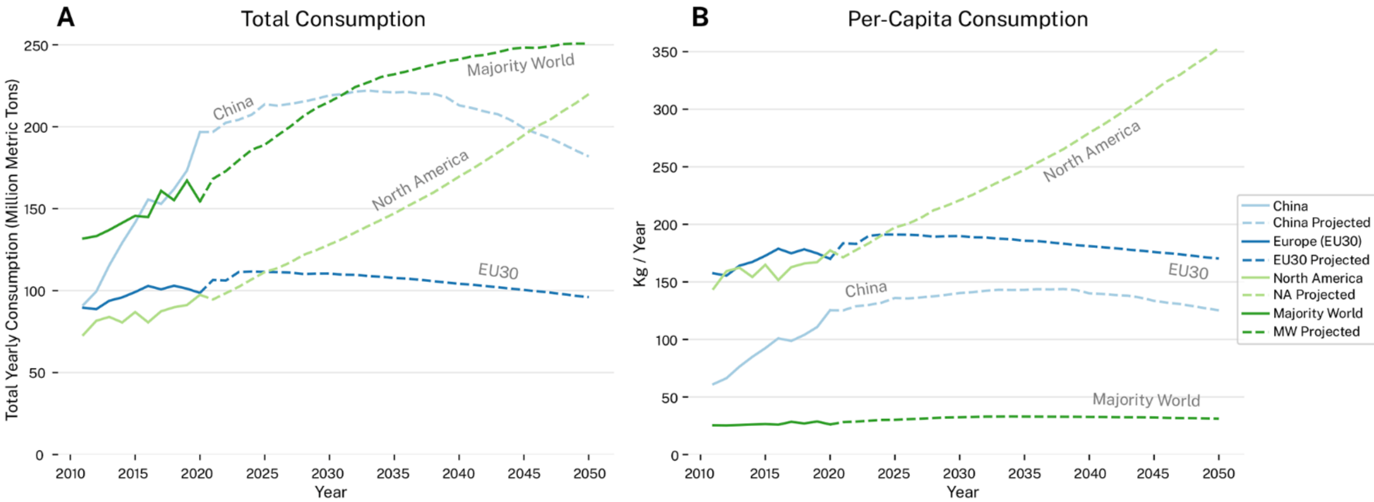

Fig. 1. Total Consumption and Per-Capita Consumption of Plastic. Global consumption of plastic with projections to 2050 by four world regions: China, European Union (EU) 30, North America (NA), and Majority World (MW). Total plastic consumption (million metric tons) (**A**) by region for all plastic sectors and polymer types and (**B**) plastic consumption per-capita (kg/year). Dashed lines represent modeled forecasts of future consumption after 2021.

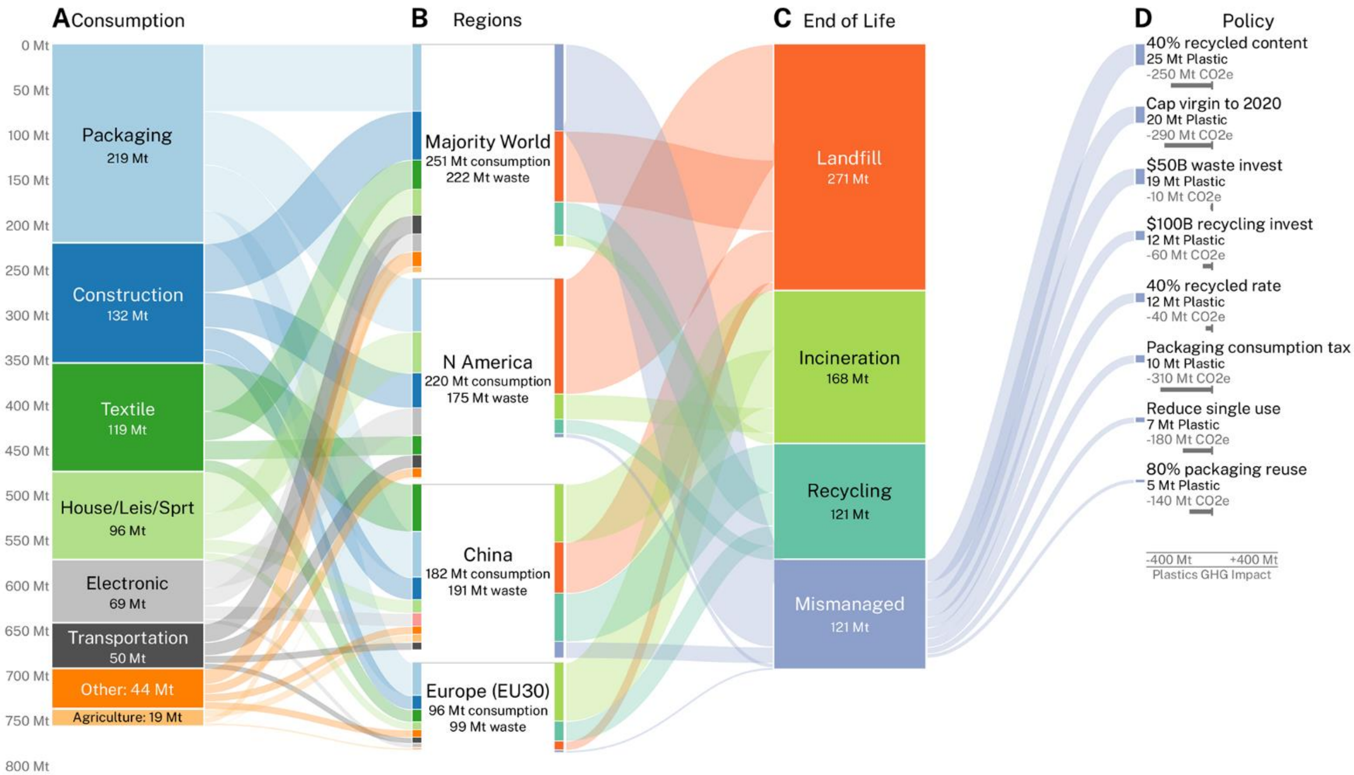

Fig. 2. caption 2050 Global Plastics Projections. Overall mass of plastics (million metric tons) predicted in 2050 to (A) be consumed in eight global sectors, (B) in four world regions and (C) in four end-of-life fates. Estimated impact of eight policy interventions (D) on reducing mass of mismanaged plastic waste and associated greenhouse gas (GHG) emissions (million metric tons CO2e) in 2050. Outcomes are depicted here for when all eight policies are implemented at the same time and include projected interactions between these policies.

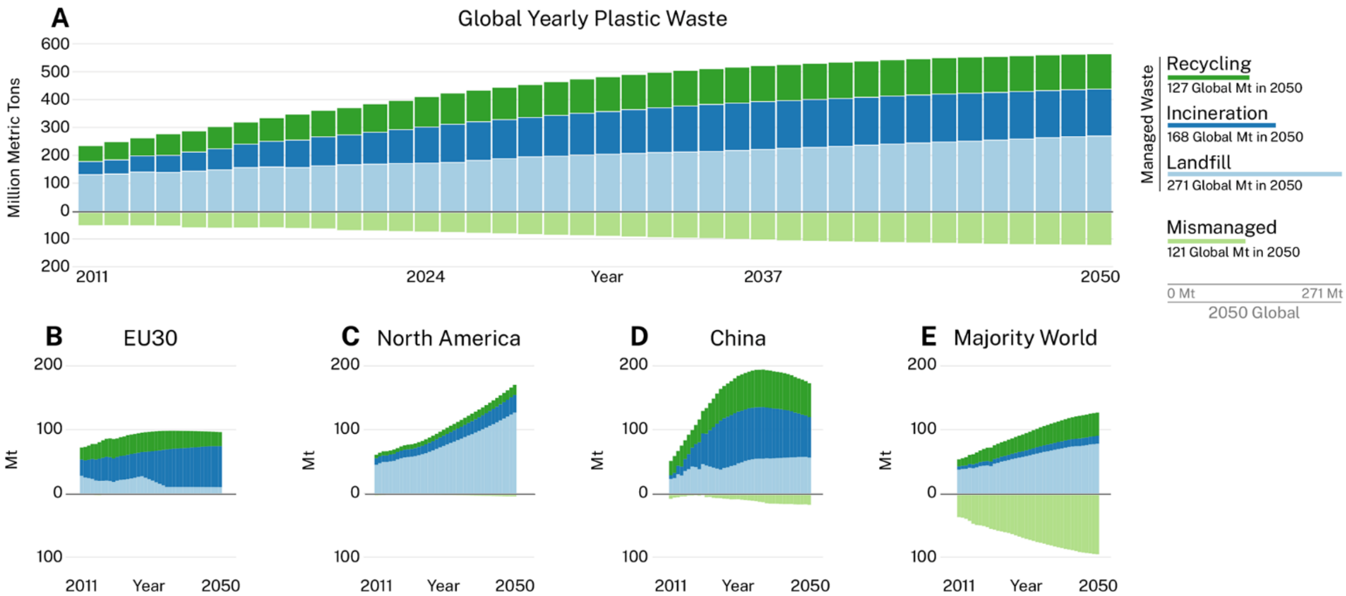

Fig. 3. Global and Regional Yearly Plastic Waste. Annual end-of-life plastic volumes by fate both (**A**) globally and in each of four world regions: (**B**) EU 30, (**C**) North America, (**D**) China, and (**E**) Majority World. Historical data is presented to 2020 and modeled under a business as usual scenario to 2050. Four categories of end-of-life plastic waste management are recognized: formal recycling, incineration, landfill, and mismanaged plastic waste.

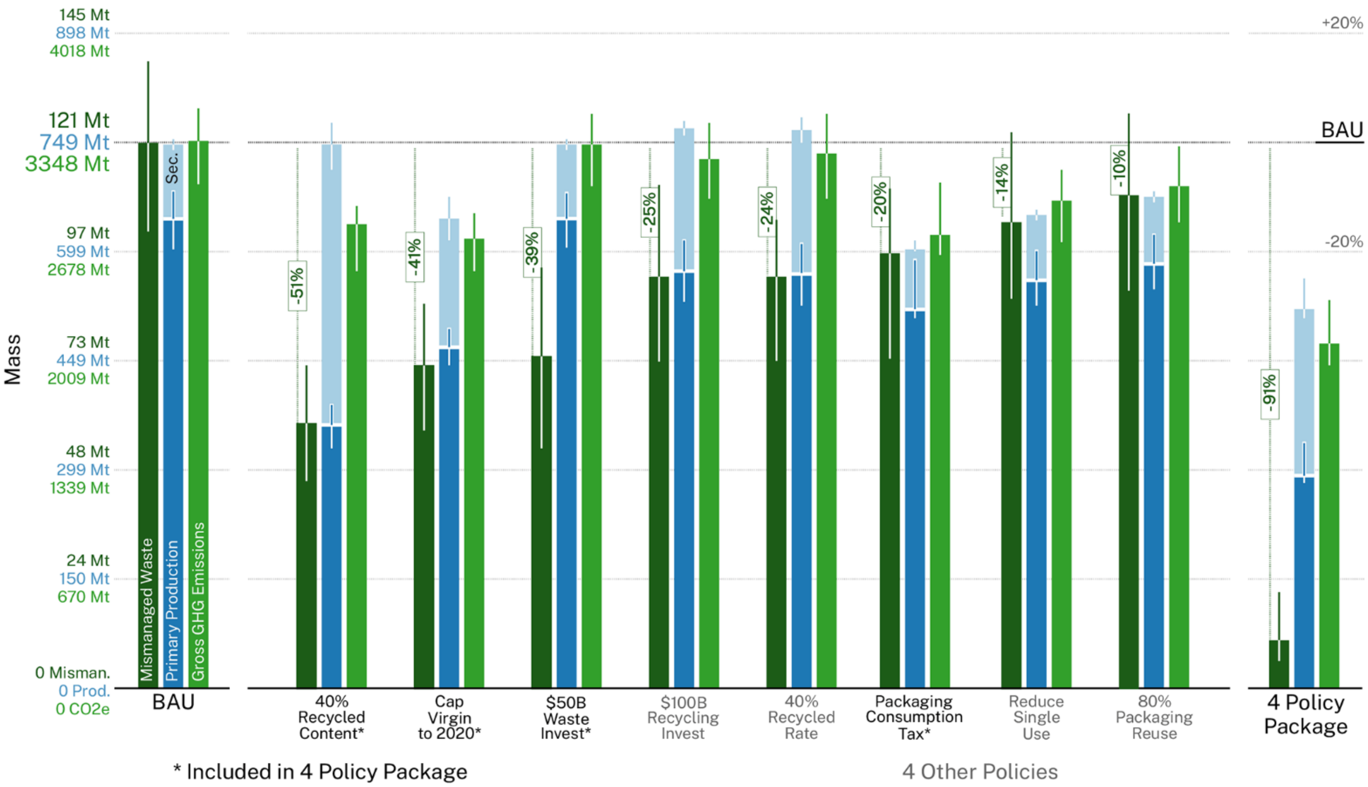

Fig. 4. Projected Impacts of Potential Policies. Projected impacts of eight policies under consideration in the United Nations plastics treaty on mismanaged plastic waste, plastic production (primary and secondary), and gross plastic-related greenhouse gas (GHG) emissions. The impact of each policy is measured relative to business as usual (BAU) in 2050. Bars show best assumption parameters as indicated in our online tool while lines at the top of those bars show 95% confidence interval from Monte Carlo (500 trials per policy). Policies tested include: requiring a minimum of 40% recycled plastic content; capping global virgin plastic production at 2020 levels; investing $50B total in waste management infrastructure; instituting a tax on plastic packaging; investing $100B total in recycling infrastructure; mandating a 40% rate of plastic waste collection for recycling; reducing single-use plastic packaging; and requiring a minimum 80% reuse rate for all plastic packaging. One of many possible policy packages is considered here that combines the impacts of four such policies (i.e., 40% recycled content; 2020 virgin production cap; $50B waste management investment; and a plastic packaging tax) while taking into account their interactions. Collectively, this policy package is projected to reduce mismanaged plastic waste by approximately 91% and greenhouse gas emissions by one third by 2050.