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Supplementary Materials for

Plastic waste inputs from land into the ocean

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Methods

Estimating per capita waste generation rates and percentage of plastic in the waste stream in 2010

The World Bank generated the most recent and most comprehensive estimates of per capita waste generation rates and percentage of plastic waste for 145 countries in the year 2005 (*5*). Of the 192 coastal countries in our analysis, waste generation rates were reported for 128 countries, and percent plastic waste for 73 countries. To estimate these quantities for the remaining countries, we applied average values for each economic classification defined by the World Bank (HIC = high income; UMI = upper middle income; LMI = lower middle income; LI = low income) based upon 2010 gross national income per capita (GNI; from http://unstats.un.org/unsd/pocketbook/World_Statistics_Pocketbook_2013_edition.pdf). One exception is China, for which the 2010 value from a more recent World Bank study was used (*23*). This study reported a lower waste generation rate (1.1 kg/person/day) than would have been assigned using China's 2010 economic classification (1.2 kg/person/day). Waste generation rates likely increased from 2005 to 2010, thus our estimates are conservative.

To project the trend of plastic in the waste stream from 2005 onwards, we developed a model to predict the annual growth rate of the percent plastic in the waste stream using measured percentage of plastic in the municipal solid waste stream in the United States from 1960 (0.4%) through 2012 (12.7%), reported by the U.S. Environmental Protection Agency (*24*) (Fig S1). This proportional growth reflects increased plastic use due, in part, to the substitution of plastic for heavier materials (i.e., glass, metal). We fit three linear models (constant, first order and second order) to the curve of annual change in percent plastic versus time in the United States. The constant rate of increase (0.19% per year, standard error 0.0623%) was the best fit as determined by the lowest Akaike Information Criterion (AIC) score. This fractional increase, applied annually to each country in the study from 2005 onwards, is conservative compared to the growth in global plastic resin production (average ~5% per year from 1960 to 2011; *3*).

Estimating percentage of waste that is mismanaged

To quantify the percentage of mismanaged waste, we considered inadequate waste management practices separately from littering. We classified waste management practices for 81 coastal countries in which disposal methods were reported (*5*); we considered waste managed in landfills (high- and middle-income countries only) and in composting, recycling, and waste-to-energy programs to be "adequately managed". Dumps and landfills in low-income countries are described by the World Bank as, "Low-technology sites usually open dumping of wastes. High polluting to nearby aquifers, water bodies, settlements" (*5*). In addition, first-hand study of solid waste management in 14 developing countries by one of the authors (T. R. Siegler) supports the assertion that landfills in low-income countries are not adequately managed. Therefore, we considered landfills in low-income countries and all dumps to be "inadequately managed". The results were not substantially different if landfills in low-income counties were considered adequately managed or if those data were removed altogether.

We developed a logistic regression model to estimate the percentage of waste that is inadequately managed in each country. We modeled the ratio of adequate to inadequate waste management using data on waste disposal methods, economic classification and geographic region (as defined by the World Bank) for 81 countries for which we had complete data (*5*). We explored the effect of 2010 GNI and geographic region on the probability of inadequate management. We were also concerned about the variation in knowledge across the reporting countries on the fate of waste. In some cases the "Other" category of waste disposal methods accounted for as much as 94% of the total reported fates, although the median share of the reported fates in the Other category was 0.015%. We accounted for this by using the ratio of waste in the Other category to the total waste as a weight for the data in the regression, thus down-weighting data where there was significant uncertainty with respect to fate. Based on AIC scores, the best model used both GNI and region (Table S4). As expected, the probability of inadequate disposal of waste decreased with increasing income. Four of the regions had significantly different disposal behavior; two regions (Europe and Central Asia (ECA) and Latin America and the Caribbean (LCR)) had a lower inadequate management fraction than expected based on income alone, while two regions (East Asia and Pacific (EAP) and Middle East and North Africa (MENA)) had a higher inadequate management fraction than expected (Table S5). Using this fitted relationship we predicted the mean percentage of inadequately managed waste for the remaining countries, including a standard error.

Litter studies are difficult to synthesize because they are typically designed to evaluate counts of particular items and rarely report mass, and they vary substantially in methodology, which limits comparison between studies. We estimated percentage of waste littered using the only available national estimate of litter mass (*25*), which reported 4.17 million MT of litter generated in the United States in 2008, equivalent to approximately 2% of national waste generation (*24*). For each country we estimated 2% of the mass of total waste generated is littered. Although littering is ill-defined in the absence of formal waste management, in countries where waste management infrastructure is robust, litter can have a measurable impact (e.g., the United States and countries in the European Union).

Estimating the input of mismanaged plastic waste to the ocean

Some percentage of the total mismanaged plastic waste (inadequately managed plus litter) enters the ocean and becomes marine debris. To our knowledge no direct estimates of this conversion rate exist. The percent of mismanaged waste entering the ocean is highly variable and dependent on local factors such as weather conditions (e.g., rain storms flushing debris from waterways), topography and vegetation, and infrastructure that removes or traps mismanaged waste before it reaches the ocean, such as municipal street sweeping, beach cleaning and stormwater catchment devices.

To loosely bound the estimate of the mass of plastic waste that enters the ocean we used municipal water quality data from the San Francisco Bay (California) watershed. In the context of water quality assessment, litter and "trash" have been identified as contaminants of concern (*26*), driving initiatives to quantify capture rates by infrastructure at municipal or county levels. Total Maximum Daily Loads (TMDLs; the maximum quantity of a pollutant that can enter a waterway while still allowing the waterway to meet its water quality standards (Section 303(d) of the Clean Water Act)) are developed for impaired waterways with water quality below applicable standards. Trash TMDLs have been developed for, or are under development for, 73 waterways in California, the Anacostia River watershed in Washington, DC and Maryland, and the Duck Creek in Mendenhall Valley, Alaska (*27-29*). The Trash TMDL, where defined and typically for trash greater than 5 mm in size, is set at zero.

Baseline and monitoring data were collected in 71 municipalities in the San Francisco Bay watershed to evaluate the effectiveness of measures designed to meet the zero trash TMDL (note that no such data exist for the Washington, DC/Maryland and Alaska regions) (*29*). The baseline trash loading rate (gallons), the quantity of trash (gallons) collected by street sweeping, storm drain catchment, and pump station cleaning, and the trash loading rate (gallons/year, defined as baseline minus the trash collected) were documented from each report. For each municipality, the percentage of trash that was not collected by street sweeping or catchment was also reported. The minimum, maximum and mean, computed over 71 municipalities, of the quantity of trash collected by street sweeping, catchments or pump stations, and the uncaptured residual, are given in Table S6. From these data an estimated 61% of trash (all materials littered in the watershed), was uncaptured by street sweeping or catchments, and thus available to enter waterways that ultimately drain to the Pacific Ocean. In our study, we assumed a more conservative range of conversion rates (15%, 25%, 40%) of mismanaged plastic waste to marine debris in order to estimate the mass of plastic that entered the ocean from land-based waste.

Projections from 2010 to 2025

To extend our estimates of the mass of mismanaged plastic waste to the year 2025, we utilized population projections for each country for 2015, 2020 and 2025 (*13*). We held 2010 per capita waste generation rates constant until 2025 when projected rates (given for 128 countries (*5*) and using averages by economic category for the remainder) were applied. We projected the percentage of plastic waste using the method described above, and used a business-as-usual approach assuming no improvements in waste management infrastructure (i.e., mismanaged waste fractions were constant). We chose this approach because of the inability to predict future infrastructure development, and because it provided a framework to examine the effect of potential mitigation strategies such as a reduction in mismanaged waste through infrastructure development.

To determine the size of coastal populations, gridded population density raster data was downloaded for use in ArcMap 10.1® for 2010 and 2015 (*30*). A 50 km buffer was drawn around the world’s coastlines, and the gridded population raster data was clipped to this buffer. This allowed us to calculate a coastal (within 50 km of the coastline) population for each country. To project the coastal populations forward from 2015 we assumed that the coastal populations would increase at a rate equal to the total projected population increase for each country.

Because the fraction of inadequately managed waste and percent plastic in the waste stream were derived from predictive models, as described above, we used the standard error associated with these fits to generate error bars on the 2025 projections of the mass of mismanaged waste available to become marine debris. For each pentad with population growth data we randomly generated 1000 values of both the mismanagement fraction and the plastic percentage from normal distributions with the mean and standard deviation defined using the mean and standard error associated with the respective predictive model. The error bars in Figure 1 describe the minimum and maximum value (from the 1000 scenarios) of the mass of mismanaged waste for a particular year.

Supplementary text

Comparison of global plastic input from mismanaged waste to ocean estimates of floating plastic debris

Cozar et al. (16) estimated the mass of floating plastic debris (7,000 – 35,000 tons) from data collected using surface-towed plankton nets. Plastic debris collected in these nets is typically microplastics, 0.33 mm – 5 mm in size. Eriksen et al. (17) reported 35,540 tons of floating microplastics from plankton net data, and 233,400 tons of "larger plastic items" (> 20 cm in size) from shipboard visual survey data. Both estimates of the mass of net-collected plastic debris, and the combined estimate from net plus visual survey data, are orders of magnitude smaller than our estimate of 4.8 to 12.7 million tonnes (5.3 to 14.0 million tons) of plastic entering the ocean in 2010 from land-based waste. Our estimate includes all plastic materials (including those that sink) in all size classes, whereas the published ocean estimates only compute the mass of floating plastic in a particular size class (or classes). In addition, we estimate the input of plastic waste in a single year (2010), while the ocean estimates represent an accumulation of floating plastic debris over an unknown time period (in part because the fragmentation and degradation rates of plastic in the ocean, and therefore the "age" of debris collected, are unknown).

Future projections

Our results indicate China had the largest mass of mismanaged plastic waste in 2010, similar to previously reported trends (*20,23*). By 2025, South Asia (e.g., India) is predicted to have a large increase in the mass of mismanaged plastic waste. In addition, two African countries (Nigeria and Senegal) showed large population growth and, therefore, increased mismanaged waste. Following projected trends through 2100 of large population growth, urbanization and increased waste generation, the forethought to develop infrastructure to adequately manage waste in African countries could mitigate increasing future inputs of plastic into the marine environment.

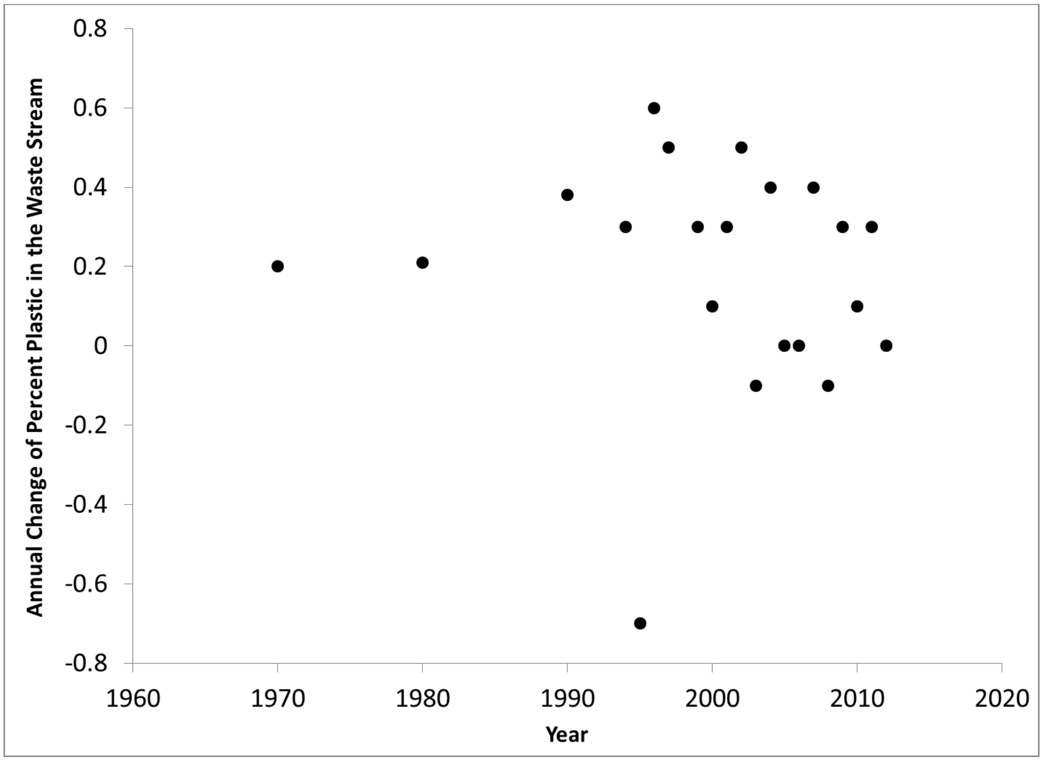

Figure S1: Annual change of percent plastic in municipal solid waste in the United States as a function of year, 1960 – 2012 (*24*), illustrating a mean annual increase of 0.19%.

Table S1: Annual and cumulative quantities (millions of metric tons (MMT)) of mismanaged plastic waste and plastic marine debris (assuming three different conversion rates) for 2010-2025.

Year	Mismanaged plastic waste [MMT/year]	15% marine debris (MMT)	25% marine debris (MMT)	40% marine debris (MMT)
2010	31.9	4.8	8.0	12.7
2015	36.5	5.5	9.1	14.6
2020	41.3	6.2	10.3	16.5
2025	69.9	10.5	17.5	28.0
Cumulative	618.7	92.8	154.7	247.5

Table S2. Top 20 countries ranked by mass of mismanaged plastic waste in 2010 and 2025, with percent increase in coastal population from 2010 to 2025. MMT, million metric tons

	Year 2010		Year 2025		
Rank	Country	Mismanaged plastic waste [MMT/year]	Country	Mismanaged plastic waste [MMT/year]	% pop. change since 2010
1	China	8.82	China	17.81	3.7%
2	Indonesia	3.22	Indonesia	7.42	11.9%
3	Philippines	1.88	Philippines	5.09	26.0%
4	Vietnam	1.83	Vietnam	4.17	13.3%
5	Sri Lanka	1.59	India	2.88	18.7%
6	Thailand	1.03	Nigeria	2.48	45.1%
7	Egypt	0.97	Bangladesh	2.21	18.5%
8	Malaysia	0.94	Thailand	2.18	5.4%
9	Nigeria	0.85	Egypt	1.94	25.0%
10	Bangladesh	0.79	Sri Lanka	1.92	9.0%
11	South Africa	0.63	Malaysia	1.77	23.6%
12	India	0.60	Pakistan	1.22	26.6%
13	Algeria	0.52	Burma	1.15	11.1%
14	Turkey	0.49	Algeria	1.02	18.4%
15	Pakistan	0.48	Brazil	0.95	10.6%
16	Brazil	0.47	South Africa	0.84	7.2%
17	Burma	0.46	Turkey	0.79	16.2%
18	Morocco	0.31	Senegal	0.74	44.3%
19	Korea, North	0.30	Morocco	0.71	14.1%
20	United States	0.28	North Korea	0.61	5.0%

Table S3: The effect of a variety of mitigation strategies on the amount of mismanaged plastic waste generated and the amount of plastic waste entering the ocean as marine debris in 2025 assuming three different conversion rates. MMT, million metric tons

	Mitigation strategy	Reduction	Mismanaged plastic waste [MMT/year]	15% marine debris (MMT)	25% marine debris (MMT)	40% marine debris (MMT)
	No intervention	0%	69.1	10.4	17.3	27.7
1	Reduce mismanaged waste by 50% in Top 20	41%	41.0	6.2	10.3	16.4
2	Reduce mismanaged waste by 50% in Top 10	34%	45.7	6.9	11.4	18.3
3	Reduce mismanaged waste by 50% in Top 5	26%	50.9	7.6	12.7	20.4
4	Reduce mismanaged waste by 85% in Top 35	75%	17.4	2.6	4.4	7.0
5	Cap at 1.7 kg/person/day and 11% plastic	26%	51.5	7.7	12.9	20.6
6	Top 10 = 0% combined with Strategy 5	77%	15.9	2.4	4.0	6.4

Table S4: Comparison of model quality, using the Akaike Information Criterion (AIC) scores, to predict the probability of inadequate waste management.

Rank	Models	AICs
4	Intercept only	5647.7
3	Intercept + GNI2010	3067.1
5	Intercept + Region	10,403.2
2	Intercept + GNI2010 + Region	2800.1
1	Intercept + GNI2010 + Region[1]	2344.5

[1]Full model with observations weighted for uncertainty

Table S5: Terms and significance for the best fit model for the probability of inadequate waste management. Coefficients correspond to the response variable on the logit scale.

Term	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**
Intercept	1.7400	0.1233	14.1110	< 2e-16
GNI2010	-0.0002	0.0000	-18.1870	< 2e-16
Region EAP	0.3267	0.2885	1.1320	0.2575
Region ECA	-1.1300	0.1515	-7.4570	0.0000
Region LCR	-1.7130	0.1360	-12.6000	< 2e-16
Region MENA	-0.4626	0.1435	-3.2230	0.0013
Region OECD	-16.8900	337.5000	-0.0500	0.9601

Regions defined by World Bank: EAP = East Asia and Pacific; ECA = Europe and Central Asia; LCR = Latin America and the Caribbean; MENA = Middle East and North Africa; OECD = The Organization for Economic Co-operation and Development.

Table S6: Percentage of trash collected by infrastructure in the San Francisco Bay watershed (*29*), and the residual uncollected percentage that is available to enter the ocean as marine debris.

n = 71 municipalities	% total trash collected by street sweeping	% total trash collected in stormwater catchments	% total trash collected in pump stations	% total trash uncollected
Minimum	0%	1.2%	0%	36%
Maximum	61%	5.0%	16.5%	95%
Mean	34%	3.2%	1.5%	61%

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