Supplementary Materials

1 Plastic leakage to oceans

Total plastic leakage to the ocean was estimated at 15 million tonnes per year by compiling previously published sources and combining their estimates for individual contributions (Supplementary Table 1.1). Sources of ocean plastics included macroplastics (greater than 5 mm) from coastal and inland populations (including mismanaged plastic from imported waste streams); macroplastics from ocean-based sources (fisheries, shipping and aquaculture); and primary microplastics (smaller than 5 mm).

Our estimate of the total plastic load going to oceans is the highest ever published in the peer-reviewed literature (~15 million tonnes per year). Nonetheless, we believe this is still likely a conservative estimate, based on our own unpublished surveys in SE Asia as well as the age of some of the available data.

Supplementary Table 1.1. Estimated plastic leakage to oceans (tonnes per year)

Source category	Total (t)	Source
Macroplastic leakage from coastal zones	8,762,950	Jambeck et al (2015)
Macroplastic leakage from inland areas	1,200,000	Lebreton et al (2017)
Macroplastic leakage from waste exports	804,473	United Nations Commodity Trade Statistics Database (2018 data), Jambeck et al (2015) mismanagement and leakage rates
Macroplastic leakage from ocean-based sources	2,737,000	Lebreton et al (2018) based on data from Watson et al (2013), Bell et al (2017), Halpern et al (2008), FAO (2016), Ocean Conservancy (2011), Arcardis (2012) and Eunomia (2016).
Primary microplastics	1,500,000	Boucher & Friot (2017)
Total	**15,004,423**	tonnes per year plastic leakage to the ocean

Macroplastic leakage from coastal zones

Rates of waste mismanagement for 192 coastal nations were modelled by Jambeck et al. (2015). Jambeck et al. applied these mismanagement rates to the estimated volume of plastic produced by populations living within 50 km of the coast to calculate the volume of mismanaged plastic in coastal zones. To calculate the amount of plastic entering oceans, they then assumed that between 15% (low) and 40% (high) of mismanaged plastic waste was leaking to oceans. We took the mid-point (27.5%) of this range as our estimated leakage rate to the ocean: applied to the mismanaged plastic waste volumes estimated for each country's coastal population, provided in the supplementary materials of Jambeck et al. (2015), this yields an estimate of 8.76 million metric tonnes (Mt) of plastic per annum (range 4.78 - 12.75 Mt) entering oceans from coastal populations (Supplementary Table 1.2).

Supplementary Table 1.2. Estimated plastic leakage to oceans (tonnes per year) from coastal populations of the top 20 polluting countries, as ranked by Jambeck et al., 2015. Mid point assumes 27.5% of mismanaged plastic waste enters oceans, lower bound assumed 15%, upper bound assumes 40%.

Country		**Mid-Point (t)**	**Lower bound (t)**	**Higher bound (t)**
1	China	2,425,422	1,322,958	3,527,887
2	Indonesia	884,635	482,528	1,286,742
3	Philippines	518,006	282,549	753,463
4	Vietnam	504,300	275,073	733,528
5	Sri Lanka	437,574	238,677	636,471
6	Thailand	282,628	154,161	411,096
7	Egypt	265,928	145,052	386,805
8	Malaysia	257,625	140,523	374,727
9	Nigeria	234,160	127,724	340,597
10	Bangladesh	216,515	118,099	314,931
11	South Africa	173,251	94,501	252,002
12	India	164,950	89,973	239,928
13	Algeria	143,153	78,083	208,222
14	Turkey	133,633	72,891	194,375
15	Pakistan	132,136	72,074	192,197
16	Brazil	129,636	70,711	188,562
17	Myanmar	126,024	68,740	183,308
18	Morocco	85,285	46,519	124,050
19	North Korea	83,690	45,649	121,731
20	United States	75,742	41,314	110,170
Sum		**7,274,294**	**3,967,797**	**3,967,797**
Sum of all 192 nations		**8,762,950**	**4,779,791**	**12,746,109**

Macroplastic leakage from inland areas

We used the Lebreton et al (2017) estimate of plastic inputs from inland areas (> 50km from coastline) to oceans. They estimated inland populations contributed between 0.79 and 1.52 Mt per year of plastic to oceans via river transport. We took the mid-point[1] calculated from the average of lower and upper range, 1.2 Mt per year.

[1] In the absence of information on the underlying distribution of source data published as ranges, we have assumed the midpoint as a proxy of median value.

Macroplastic leakage from waste exports

Per capita generation of plastic waste is much larger in high-income countries. For example, OECD countries are estimated to generate an average of 2.2 kg per capita per day *versus* sub-Saharan Africa at an average of 0.65 kg per capita per day (Hoornweg and Bhada-Tata, 2012). High labour costs and low profitability from plastic recycling has driven the growth of plastic waste exports from high-income nations to low and middle-income nations whose recycling industries operate at lower cost (Brooks et al., 2018). However, less-developed waste management infrastructure in these destination countries results in higher waste mismanagement rates than in the wealthier source countries (Jambeck et al., 2015). The practice of exporting waste therefore potentially leads to additional plastic leakage to oceans through the mismanagement of plastic waste in destination countries, and likely exacerbates other harmful impacts resulting from, e.g., the uncontrolled burning of waste (GAIA, 2019).

We estimated the leakage of exported plastic waste to oceans using trade data (UN Trade Statistics) and Jambeck et al's estimates of waste mismanagement rates in destination countries (Jambeck et al. 2015). We extracted UN trade data for 2018 (imported and exported) under the commodity code 3915, "Waste, parings and scrap, of plastics"[2]. We based the analysis on records from 2018 as it is the only year of data available since the implementation of strict new waste import restrictions in China, historically the largest importer of plastic waste (Brooks et al., 2018). We extracted official trade records for plastic imports and exports by both reporter and partner trade nations. We compared the volume of plastic traded from paired reporter-partner reports and took the higher of the two reported figures to limit underreporting and fill gaps where only one nation reported trade data. We calculated that in 2018, for all records available for extraction on 26th July 2019, an estimated 9.4 Mt of plastic waste was traded globally.

For each plastic importing nation, we applied estimated rates of waste mismanagement from Jambeck et al. (2015) to their imported plastic waste volumes, then calculated potential leakage to oceans using the mid-point and range of leakage rates used above (27.5%; range 15% - 40%). Landlocked nations were assumed to have a leakage rate equal to zero. The estimated volume of plastic waste potentially leaking to oceans was summed for each exporting nation, based on the countries to which waste was sent, to estimate their contribution to ocean plastic pollution through exported waste. By summing these estimates across all exporting nations, our analysis reveals an additional 0.80 Mt of macroplastic (range 0.44-1.18 Mt) potentially entering oceans every year due to plastic waste export and mismanagement (Supplementary Table 1.3).

We recognise there is a fluid international policy situation as other nations join China in banning some traded waste, and the assumption that mismanagement rates of imported plastic waste is equal to that occurring within domestic waste management systems is unverified. Therefore, we consider these figures as indicative of the potential for mismanagement to occur and stress that further research is required to quantify plastic leakage to oceans via the waste trade.

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[2] Available from: https://www.taricsupport.com/nomenclatuur/3915000000.html

Supplementary Table 1.3. Estimated plastic leakage to oceans (tonnes per year) from plastic exports for the top 20 countries as ranked by plastic mass exported (left) and leaked to oceans via exports (right). 'Kg per capita' columns show kg of exported plastic per capita (left) and kg of exported plastic per capita potentially leaking to oceans via waste exports (right). These estimations are based on data from UN trade statistics for the 2018 and Jambeck et al. (2015).

	Top 20 exporters	**Tonnes (2018)**	**Kg per capita (2018)**	**Top 20 polluters via leakage to oceans from exported plastic waste**	**Tonnes (2018)**	**Kg per capita (2018)**
1	Germany	1,266,787	15	Japan	143,243	1.1
2	United States	1,217,145	4	United States	142,360	0.4
3	Japan	1,035,421	8	Germany	79,277	1.0
4	United Kingdom	756,106	11	United Kingdom	63,514	0.9
5	France	441,705	7	China - Hong Kong SAR	57,065	7.7
6	Netherlands	344,419	20	Thailand	28,415	0.4
7	Mexico	323,338	3	Marshall Islands[3]	20,562	352.0
8	China - Hong Kong SAR	302,511	41	Australia	19,818	0.8
9	Italy	274,870	5	Spain	19,794	0.4
10	Poland	231,095	6	Netherlands	18,973	1.1
11	Austria	206,644	23	Indonesia	17,200	0.1
12	Canada	197,545	5	South Korea	15,477	0.3
13	Thailand	196,463	3	Saudi Arabia	12,665	0.4
14	Spain	187,411	4	Canada	10,428	0.3
15	Slovenia	128,308	62	Mexico	10,354	0.1
16	Australia	127,381	5	Poland	9,798	0.3
17	Czech Rep.	121,512	11	China	9,304	0.0
18	Indonesia	106,576	0	Italy	9,286	0.2
19	Switzerland	99,412	12	France	8,961	0.1
20	Sweden	96,215	10	Philippines	8,693	0.1
Global total traded		**9,403,457**		**Global total leakage**	**804,473**	
Total from the top 20		**7,660,862**		**Total from the top 20**	**705,187**	
Proportion of plastic waste exports generated from top 20 exporters		**81.5%**		**Estimated proportion of plastic waste exports leaking to oceans**	**8.6%**	

[3] The per capita figure for the Marshall Islands is an outlier relative to larger countries due to the fact that their waste management, in common with most other small island nations, relies disproportionately on exports.

Macroplastic leakage from ocean-based sources

We used the estimations for ocean-based sources of marine plastic pollution estimated by Lebreton et al (2018). We took the mid-point calculated from the average of lower and upper ranges for fishing, aquaculture and shipping as outlined in Supplementary Table 6 of Lebreton et al (2018) (Supplementary Table 1.4).

Plastic waste inputs from fishing were derived from fishing effort hotspots using data from Bell et al (2017) and Watson et al (2013). Estimates for aquaculture were derived from the UN FAO database for mariculture (ocean-based aquaculture; http://www.fao.org/aquastat/en/). Finally, estimates for shipping were estimated using gridded shipping frequency data from Halpern et al (2008). For further details on how these estimates were calculated, see the supplementary materials from Lebreton et al (2018)[4].

Supplementary Table 1.4. Estimated plastic leakage to oceans (tonnes per year) from ocean-based sources, as estimated by Lebreton et al (2018).

Sources	**Range**	**Mid-point**
Fishing	290,000 – 3,500,000	1,895,000
Shipping	100,000 – 1,400,000	750,000
Aquaculture	14,000 – 170,000	92,000
Total		**2,737,000**

Primary microplastics

While the degradation of macroplastics into fragments is the major source of ocean microplastics, primary microplastics – those directly released into the environment as particles smaller than 5 mm – represent an additional source of debris. Boucher and Friot (2017) estimated 1.5 Mt of microplastics (range 0.8 Mt – 2.5 Mt) entering oceans per year from the laundering of synthetic textiles, abrasion of car tyres, fallout of city dust, abrasion of road markings, release of marine coatings, microbeads from cosmetics, and spills of plastic pellets.

We used the reported per cent contributions to estimate the volume for each of the major source categories reported (Supplementary Table 1.5). For further details on how estimates were calculated, see the original report by Boucher & Friot (2017).

[4] Available from https://static-content.springer.com/esm/art%3A10.1038%2Fs41598-018-22939-w/MediaObjects/41598_2018_22939_MOESM1_ESM.pdf

Supplementary Table 1.5. Primary microplastics leakage to oceans (tonnes per year), as estimated by Boucher & Friot (2017).

Sources	%	Total
Laundering of synthetic textiles	35%	525,000
Abrasion of car tyres	28%	420,000
Fallout of city dust	24%	360,000
Abrasion of road markings	7%	105,000
Release of marine coatings	3.7%	55,500
Release of microbeads from cosmetics	2%	30,000
Spills of plastic pellet	0.3%	4,500
Total		**1,500,000**

2 Plastic pollution damage costs

To calculate the economic value of the damage caused to the environment from the plastics industry, we combined information from three sources; UNEP (2014), Beaumont et al. (2019) and Zheng and Suh (2019). While UNEP considered the decline in natural capital as a result of plastics across their life cycle, Beaumont et al. (2019) assessed the impact of ocean plastics on marine ecosystem services specifically and Zheng and Suh (2019) assessed the contribution to greenhouse gases. The latter two resources were considered more recent and comprehensive estimates of specific aspects of environmental damage and were therefore chosen to supersede the UNEP life cycle analysis in their respective categories. The UNEP breakdown of costs by commercial sector and cost category was applied *pro rata* to the other data to assign aggregate costs to particular product streams.

Land and water pollutants / Additives, Water use, Air pollutants and Land disamenity

UNEP (2014) applied a natural capital approach to quantify the upstream (plastic inputs to manufacturing) and downstream (post manufacturing) impacts of plastic products across industries. We extracted the predicted contribution of natural capital costs from each sector from the figures provided in their Appendix 1: Sector Specific Results (UNEP, 2014, page 55-76) using a web based plot digitiser (https://automeris.io/WebPlotDigitizer/).

Attempts to quantify these upstream and downstream impacts are hindered by the absence of robust data across the complexity of global industries and the variable scales of environmental impacts. Therefore, where more comprehensive or recent damage estimates were available, we substituted these for the equivalent categories in UNEP (2014); 'Marine Impacts' was superseded by Beaumont et al.'s *Marine ecosystem services delivery* (2019); 'Greenhouse gases' was replaced by Zheng and Suh's greenhouse gas analysis (2019); UNEP categories 'Terrestrial pollutants to land and water' and 'Additives' were summed for brevity; UNEP categories 'Water use', 'Air pollutants' and 'Land disamenity' were left unchanged.

Declining marine ecosystem services delivery

After Beaumont et al (2019), we assume marine ecosystem services provided benefits to society approximating US$ 49 trillion per year (Costanza et al., 2014). Following their estimates of a 1 - 5% decline in marine ecosystem service delivery due to the stock of marine plastics in 2011, this decline equals an estimated US$ 500 - 2,500 billion annual loss. We take the mid-point estimate of their calculations to assume an annual loss worth US$ 1.5 trillion. To allocate the cost of lost marine ecosystem services to different commercial sectors, the sectoral allocation of costs in the 'maritime services' category in the UNEP report was applied *pro rata* to the US$ 1.5 trillion total (see below for UNEP data extraction methods).

Greenhouse gas contributions

To estimate the environmental costs of greenhouse gases (GHG) emitted by the current plastics economy, we used published estimates of the total GHG emissions from the plastics industry and the estimated social costs of carbon. Zheng and Suh (2019) estimate that the entire lifecycle of conventional plastics generated an estimated 1.665 $GtCO_2$ of emissions in 2015, net of plastic recycling carbon credits (0.116 $GtCO_2$ in credits).

Ricke et al. (2018) estimate a global social cost of carbon of US$ 417 per ton (median, range US$ 177–805 per tCO_2). By multiplying the emissions by the global social cost of carbon, we estimated the expected economic damage associated with greenhouse gas emissions from the plastics economy to be US$ 694.3 billion in 2015 (Table 2.1). To allocate greenhouse gas emissions to different commercial sectors, the ratio of sectoral costs in the 'greenhouse gas emissions' category of the UNEP report (2014) was applied *pro rata* to the total social cost of carbon calculated above.

Supplementary Table 2.1. Estimated damage cost of plastic pollution broken down by industry sector (US$ million per year).

Sector	Total annual loss	Ocean damage	Greenhouse gases	Land pollutants	Water use	Air pollution	Land disamenity
Food	**783,162**	619,104	157,179	5,304	1,050	303	222
Soft drinks	**355,848**	270,440	81,845	2,767	548	152	96
Retail	**232,780**	177,673	52,828	1,769	348	99	63
Non-durable household goods	**190,021**	121,462	65,649	2,284	424	118	84
Personal products	**87,883**	68,200	18,869	631	125	35	24
Clothing and accessories	**98,981**	58,176	39,124	1,314	252	72	43
Toys	**80,080**	48,546	30,182	1,065	195	56	36
Footwear	**79,114**	43,829	33,839	1,133	217	64	32
Restaurants	**51,769**	42,060	9,304	313	62	17	14
Tobacco	**27,856**	22,209	5,426	171	34	9	7
Athletic goods	**26,678**	15,330	10,871	377	69	20	11
Medical and pharmaceutical products	**16,717**	12,775	3,778	127	25	7	5
Consumer electronics	**14,131**	197	13,323	487	86	24	15
Furniture	**69,097**	-	66,151	2,345	415	118	68
Automobiles	**66,965**	-	63,318	2,972	453	128	94
Durable household goods	**44,698**	-	42,620	1,653	281	83	61
Total	**2,225,781**	**1,500,000**	**694,305**	**24,712**	**4,584**	**1,305**	**875**
Data Source		*Beaumont et al (2019)*	*Zheng and Suh (2018), Ricke et al (2019)*	*UNEP (2014)*	*UNEP (2014)*	*UNEP (2014)*	*UNEP (2014)*

References

Arcadis (2012). Economic assessment of policy measures for the implementation of the marine 483 strategy framework directive. Brussels: Arcadis Belgium Available at: https://ec.europa.eu/environment/enveco/water/pdf/report.pdf.

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., et al. (2019). Global ecological, social and economic impacts of marine plastic. *Marine Pollution Bulletin* 142, 189–195. doi:10.1016/j.marpolbul.2019.03.022.

Bell, J. D., Watson, R. A., and Ye, Y. (2017). Global fishing capacity and fishing effort from 1950 to 2012. *Fish and Fisheries* 18, 489–505. doi:10.1111/faf.12187.

Boucher, J., and Friot, D. (2017). Primary microplastics in the oceans: a global evaluation of sources. IUCN Available at: https://portals.iucn.org/library/sites/library/files/documents/2017-002.pdf [Accessed August 7, 2019].

Brooks, A. L., Wang, S., and Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Sci Adv* 4, eaat0131. doi:10.1126/sciadv.aat0131.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., et al. (2014). Changes in the global value of ecosystem services. *Global Environmental Change* 26, 152–158. doi:10.1016/j.gloenvcha.2014.04.002.

Eunomia (2016). Study to support the development of measures to combat a range of marine litter sources Report for European Commission DG Environment. Available at: https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/MSFD%20Measures%20to%20Combat%20Marine%20Litter.pdf.

FAO (2016). AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO). Available at: http://www.fao.org/aquastat/en/ [Accessed August 26, 2019].

GAIA (2019). Discarded: Communities on the frontlines of the global plastic crisis. Berkeley, CA: Global Alliance for Incinerator Alternatives.

Geyer, R., Jambeck, J. R., and Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Sci Adv* 3, e1700782. doi:10.1126/sciadv.1700782.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. (2008). A Global Map of Human Impact on Marine Ecosystems. *Science* 319, 948. doi:10.1126/science.1149345.

Hoornweg, D., and Bhada-Tata, P. (2012). What a Waste : A Global Review of Solid Waste Management. Washington, DC: World Bank Available at: https://openknowledge.worldbank.org/handle/10986/17388.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768. doi:10.1126/science.1260352.

Lebreton, L. C. M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications* 8, 15611.

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., et al. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Scientific Reports* 8, 4666. doi:10.1038/s41598-018-22939-w.

Ocean Conservancy (2011). Tracking Trash: 25 Years of Action for the Ocean. Available at: https://issuu.com/oceanconservancy/docs/marine_debris_2011_report_oc.

Ricke, K., Drouet, L., Caldeira, K., and Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change* 8, 895–900. doi:10.1038/s41558-018-0282-y.

UN Trade Statistics UN Comtrade Database. *United Nations Commodity Trade Statistics Database*. Available at: https://comtrade.un.org/db/default.aspx [Accessed July 26, 2019].

UNEP (2014). Valuing Plastics: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry. Division of Environmental Policy Implementation, United Nations Environment Programme Available at: http://wedocs.unep.org/handle/20.500.11822/9238 [Accessed August 5, 2019].

Watson, R. A., Cheung, W. W. L., Anticamara, J. A., Sumaila, R. U., Zeller, D., and Pauly, D. (2013). Global marine yield halved as fishing intensity redoubles. *Fish and Fisheries* 14, 493–503. doi:10.1111/j.1467-2979.2012.00483.x.

Zheng, J., and Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change* 9, 374–378. doi:10.1038/s41558-019-0459-z.