PLASTICS

Production, use, and fate of all plastics ever made

Roland Geyer,[1]* Jenna R. Jambeck,[2] Kara Lavender Law[3]

Plastics have outgrown most man-made materials and have long been under environmental scrutiny. However, robust global information, particularly about their end-of-life fate, is lacking. By identifying and synthesizing dispersed data on production, use, and end-of-life management of polymer resins, synthetic fibers, and additives, we present the first global analysis of all mass-produced plastics ever manufactured. We estimate that 8300 million metric tons (Mt) as of virgin plastics have been produced to date. As of 2015, approximately 6300 Mt of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. If current production and waste management trends continue, roughly 12,000 Mt of plastic waste will be in landfills or in the natural environment by 2050.

INTRODUCTION

A world without plastics, or synthetic organic polymers, seems unimaginable today, yet their large-scale production and use only dates back to ~1950. Although the first synthetic plastics, such as Bakelite, appeared in the early 20th century, widespread use of plastics outside of the military did not occur until after World War II. The ensuing rapid growth in plastics production is extraordinary, surpassing most other man-made materials. Notable exceptions are materials that are used extensively in the construction sector, such as steel and cement (*1*, *2*).

Instead, plastics' largest market is packaging, an application whose growth was accelerated by a global shift from reusable to single-use containers. As a result, the share of plastics in municipal solid waste (by mass) increased from less than 1% in 1960 to more than 10% by 2005 in middle- and high-income countries (*3*). At the same time, global solid waste generation, which is strongly correlated with gross national income per capita, has grown steadily over the past five decades (*4*, *5*).

The vast majority of monomers used to make plastics, such as ethylene and propylene, are derived from fossil hydrocarbons. None of the commonly used plastics are biodegradable. As a result, they accumulate, rather than decompose, in landfills or the natural environment (*6*). The only way to permanently eliminate plastic waste is by destructive thermal treatment, such as combustion or pyrolysis. Thus, near-permanent contamination of the natural environment with plastic waste is a growing concern. Plastic debris has been found in all major ocean basins (*6*), with an estimated 4 to 12 million metric tons (Mt) of plastic waste generated on land entering the marine environment in 2010 alone (*3*). Contamination of freshwater systems and terrestrial habitats is also increasingly reported (*7*–*9*), as is environmental contamination with synthetic fibers (*9*, *10*). Plastic waste is now so ubiquitous in the environment that it has been suggested as a geological indicator of the proposed Anthropocene era (*11*).

We present the first global analysis of all mass-produced plastics ever made by developing and combining global data on production, use, and end-of-life fate of polymer resins, synthetic fibers, and additives into a comprehensive material flow model. The analysis includes thermoplastics, thermosets, polyurethanes (PURs), elastomers, coatings, and sealants but focuses on the most prevalent resins and fibers: high-density polyethylene (PE), low-density and linear low-density PE, polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), polyethylene terephthalate (PET), and PUR resins; and polyester, polyamide, and acrylic (PP&A) fibers. The pure polymer is mixed with additives to enhance the properties of the material.

[1]Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA 93106, USA. [2]College of Engineering, University of Georgia, 412 Driftmier Engineering Center, Athens, GA 30602, USA. [3]Sea Education Association, Woods Hole, MA 02543, USA.
*Corresponding author. Email: geyer@bren.ucsb.edu

RESULTS AND DISCUSSION

Global production of resins and fibers increased from 2 Mt in 1950 to 380 Mt in 2015, a compound annual growth rate (CAGR) of 8.4% (table S1), roughly 2.5 times the CAGR of the global gross domestic product during that period (*12*, *13*). The total amount of resins and fibers manufactured from 1950 through 2015 is 7800 Mt. Half of this—3900 Mt—was produced in just the past 13 years. Today, China alone accounts for 28% of global resin and 68% of global PP&A fiber production (*13*–*15*). Bio-based or biodegradable plastics currently have a global production capacity of only 4 Mt and are excluded from this analysis (*16*).

We compiled production statistics for resins, fibers, and additives from a variety of industry sources and synthesized them according to type and consuming sector (table S2 and figs. S1 and S2) (*12*–*24*). Data on fiber and additives production are not readily available and have typically been omitted until now. On average, we find that nonfiber plastics contain 93% polymer resin and 7% additives by mass. When including additives in the calculation, the amount of nonfiber plastics (henceforth defined as resins plus additives) manufactured since 1950 increases to 7300 Mt. PP&A fibers add another 1000 Mt. Plasticizers, fillers, and flame retardants account for about three quarters of all additives (table S3). The largest groups in total nonfiber plastics production are PE (36%), PP (21%), and PVC (12%), followed by PET, PUR, and PS (<10% each). Polyester, most of which is PET, accounts for 70% of all PP&A fiber production. Together, these seven groups account for 92% of all plastics ever made. Approximately 42% of all nonfiber plastics have been used for packaging, which is predominantly composed of PE, PP, and PET. The building and construction sector, which has used 69% of all PVC, is the next largest consuming sector, using 19% of all nonfiber plastics (table S2).

We combined plastic production data with product lifetime distributions for eight different industrial use sectors, or product categories, to model how long plastics are in use before they reach the end of their useful lifetimes and are discarded (*22*, *25*–*29*). We assumed log-normal distributions with means ranging from less than 1 year, for packaging, to decades, for building and construction (Fig. 1). This is a commonly used modeling approach to estimating waste generation

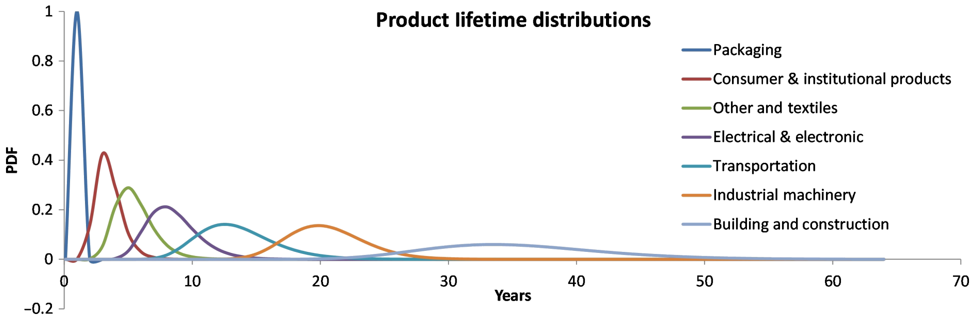

Fig. 1. Product lifetime distributions for the eight industrial use sectors plotted as log-normal probability distribution functions (PDF). Note that sectors other and textiles have the same PDF.

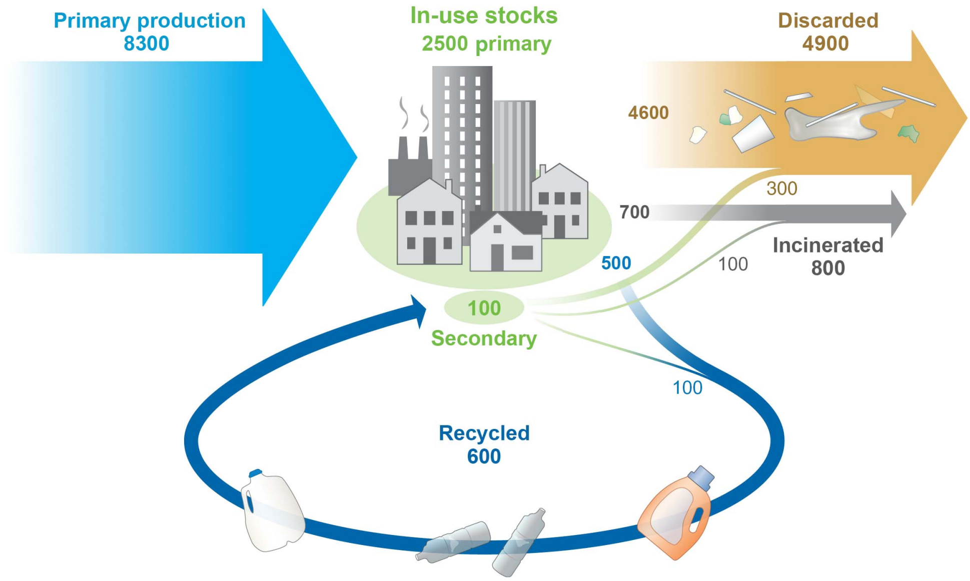

Fig. 2. Global production, use, and fate of polymer resins, synthetic fibers, and additives (1950 to 2015; in million metric tons).

for specific materials (*22*, *25*, *26*). A more direct way to measure plastic waste generation is to combine solid waste generation data with waste characterization information, as in the study of Jambeck *et al.* (*3*). However, for many countries, these data are not available in the detail and quality required for the present analysis.

We estimate that in 2015, 407 Mt of primary plastics (plastics manufactured from virgin materials) entered the use phase, whereas 302 Mt left it. Thus, in 2015, 105 Mt were added to the in-use stock. For comparison, we estimate that plastic waste generation in 2010 was 274 Mt, which is equal to the independently derived estimate of 275 Mt by Jambeck *et al.* (*3*). The different product lifetimes lead to a substantial shift in industrial use sector and polymer type between plastics entering and leaving use in any given year (tables S4 and S5 and figs. S1 to S4). Most of the packaging plastics leave use the same year they are produced, whereas construction plastics leaving use were produced decades earlier, when production quantities were much lower. For example, in 2015, 42% of primary nonfiber plastics produced (146 Mt) entered use as packaging and 19% (65 Mt) as construction, whereas nonfiber plastic waste leaving use was 54% packaging (141 Mt) and only 5% construction (12 Mt). Similarly, in 2015, PVC accounted for 11% of nonfiber plastics production (38 Mt) and only 6% of nonfiber plastic waste generation (16 Mt).

By the end of 2015, all plastic waste ever generated from primary plastics had reached 5800 Mt, 700 Mt of which were PP&A fibers. There are essentially three different fates for plastic waste. First, it can be recycled or reprocessed into a secondary material (*22*, *26*). Recycling delays, rather than avoids, final disposal. It reduces future plastic waste generation only if it displaces primary plastic production (*30*); however, because of its counterfactual nature, this displacement is extremely difficult to establish (*31*). Furthermore, contamination and the mixing of polymer types generate secondary plastics of limited or low technical and economic value. Second, plastics can be destroyed thermally. Although there are emerging technologies, such as pyrolysis, which extracts fuel from plastic waste, to date, virtually all thermal destruction has been by incineration, with or without energy recovery. The environmental and health impacts of waste incinerators strongly depend on emission control technology, as well as incinerator design and operation. Finally, plastics can be discarded and either contained in a managed system, such as sanitary landfills, or left uncontained in open dumps or in the natural environment.

We estimate that 2500 Mt of plastics—or 30% of all plastics ever produced—are currently in use. Between 1950 and 2015, cumulative waste generation of primary and secondary (recycled) plastic waste amounted to 6300 Mt. Of this, approximately 800 Mt (12%) of plastics

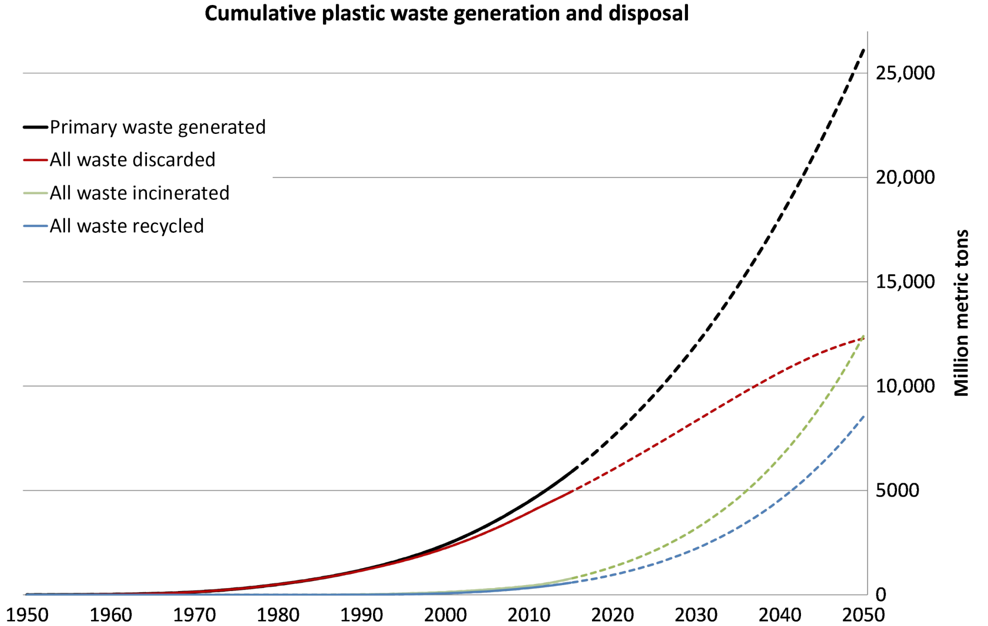

Fig. 3. Cumulative plastic waste generation and disposal (in million metric tons). Solid lines show historical data from 1950 to 2015; dashed lines show projections of historical trends to 2050.

have been incinerated and 600 Mt (9%) have been recycled, only 10% of which have been recycled more than once. Around 4900 Mt—60% of all plastics ever produced—were discarded and are accumulating in landfills or in the natural environment (Fig. 2). Of this, 600 Mt were PP&A fibers. None of the mass-produced plastics biodegrade in any meaningful way; however, sunlight weakens the materials, causing fragmentation into particles known to reach millimeters or micrometers in size (*32*). Research into the environmental impacts of these "microplastics" in marine and freshwater environments has accelerated in recent years (*33*), but little is known about the impacts of plastic waste in land-based ecosystems.

Before 1980, plastic recycling and incineration were negligible. Since then, only nonfiber plastics have been subject to significant recycling efforts. The following results apply to nonfiber plastic only: Global recycling and incineration rates have slowly increased to account for 18 and 24%, respectively, of nonfiber plastic waste generated in 2014 (figs. S5 and S6). On the basis of limited available data, the highest recycling rates in 2014 were in Europe (30%) and China (25%), whereas in the United States, plastic recycling has remained steady at 9% since 2012 (*12*, *13*, *34*–*36*). In Europe and China, incineration rates have increased over time to reach 40 and 30%, respectively, in 2014 (*13*, *35*). However, in the United States, nonfiber plastics incineration peaked at 21% in 1995 before decreasing to 16% in 2014 as recycling rates increased, with discard rates remaining constant at 75% during that time period (*34*). Waste management information for 52 other countries suggests that in 2014, the rest of the world had recycling and incineration rates similar to those of the United States (*37*). To date, end-of-life textiles (fiber products) do not experience significant recycling rates and are thus incinerated or discarded together with other solid waste.

Primary plastics production data describe a robust time trend throughout its entire history. If production were to continue on this curve, humankind will have produced 26,000 Mt of resins, 6000 Mt of PP&A fibers, and 2000 Mt of additives by the end of 2050. Assuming consistent use patterns and projecting current global waste management trends to 2050 (fig. S7), 9000 Mt of plastic waste will have been recycled, 12,000 Mt incinerated, and 12,000 Mt discarded in landfills or the natural environment (Fig. 3).

Any material flow analysis of this kind requires multiple assumptions or simplifications, which are listed in Materials and Methods, and is subject to considerable uncertainty; as such, all cumulative results are rounded to the nearest 100 Mt. The largest sources of uncertainty are the lifetime distributions of the product categories and the plastic incineration and recycling rates outside of Europe and the United States. Increasing/decreasing the mean lifetimes of all product categories by 1 SD changes the cumulative primary plastic waste generation (for 1950 to 2015) from 5900 to 4600/6200 Mt or by −4/+5%. Increasing/decreasing current global incineration and recycling rates by 5%, and adjusting the time trends accordingly, changes the cumulative discarded plastic waste from 4900 (for 1950 to 2015) to 4500/5200 Mt or by −8/+6%.

The growth of plastics production in the past 65 years has substantially outpaced any other manufactured material. The same properties that make plastics so versatile in innumerable applications—durability and resistance to degradation—make these materials difficult or impossible for nature to assimilate. Thus, without a well-designed and tailor-made management strategy for end-of-life plastics, humans are conducting a singular uncontrolled experiment on a global scale, in which billions of metric tons of material will accumulate across all major terrestrial and aquatic ecosystems on the planet. The relative advantages and disadvantages of dematerialization, substitution, reuse, material recycling, waste-to-energy, and conversion technologies must be carefully considered to design the best solutions to the environmental challenges posed by the enormous and sustained global growth in plastics production and use.

MATERIALS AND METHODS

Plastic production

The starting point of the plastic production model is global annual pure polymer (resin) production data from 1950 to 2015, published by the Plastics Europe Market Research Group, and global annual fiber production data from 1970 to 2015 published by The Fiber Year and Tecnon OrbiChem (table S1). The resin data closely follow a second-order polynomial time trend, which generated a fit of R^2 = 0.9968. The fiber data closely follow a third-order polynomial time trend, which generated a fit of R^2 = 0.9934. Global breakdowns of total production by polymer type and industrial use sector were derived from annual market and polymer data for North America, Europe, China, and India (table S2) (*12*, *13*, *19*–*24*). U.S. and European data are available for 2002 to 2014. Polymer type and industrial use sector breakdowns of polymer production are similar across countries and regions.

Global additives production data, which are not publicly available, were acquired from market research companies and cross-checked for consistency (table S3) (*17*, *18*). Additives data are available for 2000 to 2014. Polymer type and industrial use sector breakdowns of polymer production and the additives to polymer fraction were both stable over the time period for which data are available and thus assumed constant throughout the modeling period of 1950–2015. Any errors in the early decades were mitigated by the lower production rates in those years. Additives data were organized by additive type and industrial use sector and integrated with the polymer data. $P_i(t)$ denotes the amount of primary plastics (that is, polymers plus additives) produced in year t and used in sector i (fig. S1).

Plastic waste generation and fate

Plastics use was characterized by discretized log-normal distributions, $\text{LTD}_\text{i}(j)$, which denotes the fraction of plastics in industrial use sector i used for j years (Fig. 1). Mean values and SDs were gathered from published literature (table S4) (*22*, *25*–*29*). Product lifetimes may vary significantly across economies and also across demographic groups, which is why distributions were used and sensitivity analysis was conducted with regard to mean product lifetimes. The total amount of primary plastic waste generated in year t was calculated as $\text{PW}(t) = \Sigma_{i=1}^{8}\Sigma_{j=1}^{65}P_i(t-j)\cdot\text{LTD}_i(j)$ (figs. S3 and S4). Secondary plastic waste generated in year t was calculated as the fraction of total plastic waste that was recycled k years ago, $\text{SW}(t) = [\text{PW}(t-k) + \text{SW}(t-k)][\text{RR}(t-k)]$, where k is the average use time of secondary plastics and $\text{RR}(t-k)$ is the global recycling rate in year $t-k$. Amounts of plastic waste discarded and incinerated are calculated as $\text{DW}(t) = [\text{PW}(t) + \text{SW}(t) \cdot \text{DR}(t)$ and $\text{IW}(t) = [\text{PW}(t) + \text{SW}(t)] \cdot \text{IR}(t)$, with $\text{DR}(t)$ and $\text{IR}(t)$ being the global discard and incineration rates in year t (fig. S5). Cumulative values at time T were calculated as the sum over all $T-1950$ years of plastics mass production. Examples are cumulative primary production $\text{CP}_i(T) = \Sigma_{t=1950}^{T}P_i(t)$ and cumulative primary plastic waste generation, $\text{CPW}(T) = \Sigma_{t=1950}^{T}\text{PW}(t)$ (Fig. 3).

Recycling, incineration, and discard rates

Time series for resin, that is, nonfiber recycling, incineration, and discard rates were collected separately for four world regions: the United States, the EU-28 plus Norway and Switzerland, China, and the rest of the world. Detailed and comprehensive solid waste management data for the United States were published by the U.S. Environmental Protection Agency dating back to 1960 (table S7) (*34*). European data were from several reports by PlasticsEurope, which collectively cover 1996 to 2014 (*12*, *13*, *38*). Chinese data were synthesized and reconciled from the English version of the China Statistical Yearbook, translations of Chinese publications and government reports, and additional waste management literature (*35*, *36*, *39*–*41*). Waste management for the rest of the world was based on World Bank data (*37*). Time series for global recycling, incineration, and discard rates (fig. S5) were derived by adding the rates of the four regions weighted by their relative contribution to global plastic waste generation. In many world regions, waste management data were sparse and of poor quality. For this reason, sensitivity analysis with regard to waste management rates was conducted.

The resulting global nonfiber recycling rate increased at a constant 0.7% per annum (p.a.) between 1990 and 2014. If this linear trend is assumed to continue, the global recycling rate would reach 44% in 2050. The global nonfiber incineration rate has grown more unevenly but, on average, increased 0.7% p.a. between 1980 and 2014. Assuming an annual increase of 0.7% between 2014 and 2050 yielded a global incineration rate of 50% by 2050. With those two assumptions, global discard rate would decrease from 58% in 2014 to 6% in 2050 (fig. S7). The dashed lines in Fig. 3 are based on those assumptions and therefore simply forward projections of historical global trends and should not be mistaken for a prediction or forecast. There is currently no significant recycling of synthetic fibers. It was thus assumed that end-of-life textiles are incinerated and discarded together with all other municipal solid waste.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/7/e1700782/DC1

fig. S1. Global primary plastics production (in million metric tons) according to industrial use sector from 1950 to 2015.

fig. S2. Global primary plastics production (in million metric tons) according to polymer type from 1950 to 2015.

fig. S3. Global primary plastics waste generation (in million metric tons) according to industrial use sector from 1950 to 2015.

fig. S4. Global primary plastics waste generation (in million metric tons) according to polymer type from 1950 to 2015.

fig. S5. Estimated percentage of global (nonfiber) plastic waste recycled, incinerated, and discarded from 1950 to 2014 [(*12*, *13*, *34*–*42*) and table S7].

fig. S6. Annual global primary and secondary plastic waste generation TW (t), recycling RW (t), incineration IW (t), and discard DW (t) (in million metric tons) from 1950 to 2014.

fig. S7. Projection of global trends in recycling, incineration, and discard of plastic waste from 1980 to 2014 (to the left of vertical black line) to 2050 (to the right of vertical black line).

table S1. Annual global polymer resin and fiber production in million metric tons (*12*–*15*).

table S2. Share of total polymer resin production according to polymer type and industrial use sector calculated from data for Europe, the United States, China, and India covering the period 2002–2014 (*12*, *13*, *19*–*24*).

table S3. Share of additive type in global plastics production from data covering the period 2000–2014 (*17*, *18*).

table S4. Baseline mean values and SDs used to generate log-normal product lifetime distributions for the eight industrial use sectors used in this study (*22*, *25*–*29*).

table S5. Global primary plastics production and primary waste generation (in million metric tons) in 2015 according to industrial use sector.

table S6. Global primary plastics production and primary waste generation (in million metric tons) in 2015 according to polymer type/additive.

table S7. Additional data sources for U.S. plastics recycling and incineration.

table S8. Complete list of data sources.

REFERENCES AND NOTES

1. World Steel Association (WSA), "Steel Statistical Yearbooks 1978 to 2016;" www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook-.html.
2. U.S. Geological Survey (USGS), "Cement Statistics and Information;" https://minerals.usgs.gov/minerals/pubs/commodity/cement/.
3. J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan, K. L. Law, Plastic waste inputs from land into the ocean. *Science* **347**, 768–771 (2015).
4. D. Hoornweg, P. Bhada-Tata, C. Kennedy, Environment: Waste production must peak this century. *Nature* **502**, 615–617 (2013).
5. D. C. Wilson, *Global Waste Management Outlook* (International Solid Waste Association and United National Environment Programme, 2015).

6. D. K. A. Barnes, F. Galgani, R. C. Thompson, M. Barlaz, Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. R. Soc. B* **364**, 1985–1998 (2009).
7. M. Wagner, C. Scherer, D. Alvarez-Muñoz, N. Brennholt, X. Bourrain, S. Buchinger, E. Fries, C. Grosbois, J. Klasmeier, T. Marti, S. Rodriguez-Mozaz, R. Urbatzka, A. D. Vethaak, M. Winther-Nielsen, G. Geifferscheid, Microplastics in freshwater ecosystems: What we know and what we need to know. *Environ. Sci. Eur.* **26**, 12 (2014).
8. M. C. Rillig, Microplastic in terrestrial ecosystems and the soil? *Environ. Sci. Technol.* **46**, 6453–6454 (2012).
9. K. A. V. Zubris, B. K. Richards, Synthetic fibers as an indicator of land application of sludge. *Environ. Pollut.* **138**, 201–211 (2005).
10. R Dris, J Gasperi, C Mirande, C Mandin, M Guerrouache, V Langlois, B. Tassin, A first overview of textile fibers, including microplastics, in indoor and outdoor environments. *Environ. Pollut.* **221**, 453–458 (2016).
11. J. Zalasiewicz, Colin N. Waters, Juliana Ivar do Sul, Patricia L. Corcoran, Anthony D. Barnosky, Alejandro Cearreta, Matt Edgeworth, Agnieszka Gałuszka, Catherine Jeandel, Reinhold Leinfelder, J.R. McNeill, Will Steffen, Colin Summerhayes, Michael Wagreich, Mark Williams, Alexander P. Wolfe, Yasmin Yonan, The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. *Anthropocene* **13**, 4–17 (2016).
12. PlasticsEurope, *The Compelling Facts About Plastics: An Analysis of Plastic Production, Demand and Recovery for 2006 in Europe* (PlasticsEurope, 2006).
13. PlasticsEurope, *Plastics—The Facts 2016: An Analysis of European Plastics Production, Demand and Waste Data* (PlasticsEurope, 2016).
14. The Fiber Year, *The Fiber Year 2017: World Survey on Textiles & Nonwovens* (The Fiber Year GmbH, 2017).
15. J. Mills, "Polyester & Cotton: Unequal Competitors," Tecnon OrbiChem presentation at Association Française Cotonnière (AFCOT), Deauville, France, 6 October 2011.
16. European Bioplastics, *Bioplastics—Facts and Figures* (European Bioplastics, 2017).
17. Global Industry Analysis (GIA), "Plastic Additives: A Global Strategic Business Report" (MCP-2122, GIA, 2008).
18. S. Rajaram, "Plastic Additives: The Global Market" (PLS022B, BCC Research, 2009).
19. American Chemistry Council (ACC), *Resin Review: The Annual Statistical Report of the North American Plastics Industry* (ACC, 2009).
20. Plastemart, "China leads in growth of polymers & plastic products;" www.plastemart.com/upload/Literature/chineseplasticandpolymergrowth.asp).
21. *Indian Petrochemical Industry: Country Paper from India*, Asia Petrochemical Industry Conference, Seoul, South Korea, 7 to 8 May 2015 (Chemical and Petrochemicals Manufacturers' Association India, 2016).
22. N. H. Mutha, M. Patel, V. Premnath, Plastics material flow analysis for India. *Resour. Conserv. Recycl.* **47**, 222–244 (2006).
23. American Chemistry Council (ACC), *Resin Review: The Annual Statistical Report of the North American Plastics Industry* (ACC, 2012).
24. American Chemistry Council (ACC), *Resin Review: The Annual Statistical Report of the North American Plastics Industry* (ACC, 2013).
25. J. Davis, R. Geyer, J. Ley, J. He, T. Jackson, R. Clift, A. Kwan, M. Sansom, Time-dependent material flow analysis of iron and steel in the UK: Part 2. Scrap generation and recycling. *Resour. Conserv. Recycl.* **51**, 118–140 (2007).
26. B. Kuczenski, R. Geyer, Material flow analysis of polyethylene terephthalate in the US, 1996–2007. *Resour. Conserv. Recycl.* **54**, 1161–1169 (2010).
27. S. Murakami, M. Oguchi, T. Tasaki, I. Daigo, S. Hashimoto, Lifespan of commodities, part I: The creation of a database and its review. *J. Ind. Ecol.* **14**, 598–612 (2010).
28. D. R. Cooper, A. C. H. Skelton, M. C. Moynihan, J. M. Allwood, Component level strategies for exploiting the lifespan of steel in products. *Resour. Conserv. Recycl.* **84**, 24–34 (2014).
29. Drycleaning Institute of Australia, *International Fair Claims Guide for Consumer Textiles Products* (Drycleaning Institute of Australia, 2015).
30. R. Geyer, B. Kuczenski, T. Zink, A. Henderson, Common misconceptions about recycling. *J. Ind. Ecol.* **20**, 1010–1017 (2015).
31. T. Zink, R. Geyer, D. Startz, Toward estimating displaced production from recycling: A case study of U.S. aluminum. *J. Ind. Ecol.* 10.1111/jiec.12557 (2017).
32. A. L. Andrady, *Plastics and Environmental Sustainability* (John Wiley & Sons, 2015).
33. C. M. Rochman, M. A. Browne, A. J. Underwood, J. A. van Franeker, R. C. Thompson, L. A. Amaral-Zettler, The ecological impacts of marine debris: Unraveling the demonstrated evidence from what is perceived. *Ecology* **97**, 302–312 (2016).
34. U.S. Environmental Protection Agency (EPA), *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2012* (EPA, 2014).
35. National Bureau of Statics of China, "Annual Data, China Statistical Yearbook, 1996-2016;" (www.stats.gov.cn/ENGLISH/Statisticaldata/AnnualData/).
36. M. Zhan-feng, Z. Bing, China plastics recycling industry in 2008. *China Plastics* **23**, 7 (2009).
37. D. Hoornweg, P. Bhada-Tata, *What a Waste: A Global Review of Solid Waste Management* (Urban Development Series Knowledge Papers, World Bank, 2012).
38. Consultic, *Post-Consumer Plastics Waste Management in European Countries 2014 – EU28 + 2 Countries*, Final report, PlasticsEurope, October 2015.
39. R. Linzner, S. Salhofer, Municipal solid waste recycling and the significance of the informal sector in urban China. *Waste Manage. Res.* **32**, 896–907 (2014).
40. National Development and Reform Commission of China, "Annual Report on Comprehensive Utilization of Resources in China 2014;" http://hzs.ndrc.gov.cn/zhly/201410/W020141015504221663989.pdf.
41. China Ministry of Commerce, "China Renewable Resources Recycling Industry Development Report 2016;" http://f.boolv.com/News/Image/20160811/201608110819469264.pdf.
42. U.S. Environmental Protection Agency (EPA), *Municipal Solid Waste in the Unites States: 2011 Facts and Figures* (EPA530-R-13-001, U.S. EPA, 2013).

Acknowledgments: We thank C.-J. Simon and R. Nayaran for providing polymer production data and G.L. Mahoney for designing Fig. 2. We especially thank I. Creelman and R. Song for data collection and model implementation, E. Smith for assistance in compiling the U.S. Environmental Protection Agency and China solid waste management data, S. Wang for researching China plastic waste management and translation of articles, J. Chamberlain for researching additives, and I. MacAdam-Somer for researching synthetic fibers. This work benefitted from helpful discussions with T. Siegler and C. Rochman and comments from two anonymous reviewers. **Funding:** This work was conducted within the Marine Debris Working Group at the National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, with support from Ocean Conservancy. R.G. was supported by the NSF Chemical, Bioengineering, Environmental and Transport Systems grant #1335478. **Author contributions:** R.G. led the research design, data collection, model development, calculations, interpretation of results, and writing of the manuscript; J.R.J. contributed to research design, data collection, model development, and interpretation of results; K.L.L. contributed to research design, analysis and interpretation of results, and writing of the manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 9 March 2017
Accepted 16 June 2017
Published 19 July 2017
10.1126/sciadv.1700782

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