Dynamic flows and stocks of plastics in the United States and pathways towards zero plastic pollution by 2050

By

Mengqing Kan

A thesis submitted
in partial fulfillment of the requirements
for the degree of Master of Science
(Environment and Sustainability)
at the University of Michigan
April 2021

Thesis Committee:
Professor Ming Xu, Chair
Professor Shelie Miller
Dr. Chunyan Wang

Abstract

The United States (U.S.) is the second-largest national consumer of plastics in the world, which directly leads to a large amount of plastic waste. Due to low recycling and incineration rates in the U.S., 53% of plastic waste was discarded (landfilled or mismanaged) in 2018. Scientific studies have proved that pollution from discarded plastics has a significant negative impact on the environment. This study aims to explore feasible pathways for the U.S. to achieve zero plastic pollution by 2050. This study first developed a dynamic material flow analysis (MFA) model to assess flows and stocks of nine commonly used plastic polymers in seven commodity sectors with five end-of-life pathways in the U.S. for almost seven decades (1950 – 2018). The results show that national plastic pollution increased from 176 thousand metric tons in 1950 to 34,393 thousand metric tons in 2018. Plastic packaging contributed the most to plastic pollution because it has a shorter lifespan and a higher discard rate compared with plastics in other sectors. This study also developed six scenarios to explore pathways of plastic pollution reduction from 2019 to 2050 through seven strategies including 1) adapting a national plastic grocery bag ban, 2) reducing plastic consumption, 3) improving the lifespan of plastic products, 4) increasing waste recycling rate, 5) abandoning waste export, 6) avoiding mismanaged waste leakage, and 7) increasing waste incineration rate to utilize waste resources. Even though each strategy can reduce plastic pollution to different extents, the U.S. cannot achieve the zero plastic pollution target by 2050 through implementing one strategy solely. Thus, a combined scenario that implementing multiple strategies would help the U.S. to achieve zero plastic pollution.

Keywords: Plastic pollution reduction; dynamic material flow analysis; scenario analysis; plastic waste

Table of Contents

1. Introduction

The United States (U.S.) is a major producer and consumer of plastics, accounting for about 20% of global plastics production and consumption, respectively, making it the second-largest national consumer in the world (Ryberg et al., 2018). Most of plastics are derived from petrochemicals produced from fossil fuels (Hopewell et al., 2009). The plastic production process is responsible for 3% of total U.S. energy consumption and 1% of total U.S. greenhouse gases (GHG) emissions (Posen et al., 2016). In addition to the environmental impacts caused by raw material acquisition and plastic manufacturing, there is a greater concern about plastic pollution, which is usually defined as the accumulation of plastic particles in the environment that adversely influences human health, and wildlife and its habitat (Encyclopedia Britannica, 2020). Law et al. (2020) estimated that up to 1.25 million metric tons of plastic waste were littered or illegally dumped into the environment in the U.S. in 2016. Years of mismanaged plastic waste, together with plastics accumulating in landfills, results in contamination in terrestrial (Chae and An, 2018), freshwater (Wagner and Lambert 2018), and marine environments (Barnes et al. 2018).

There is a growing number of strategies taken or proposed by governments to combat plastic pollution. In the U.S., for example, 271 local governments worked to cut the consumption of single-use plastic bags through implementing bans, taxes, fees, consumer education, mandated retailer take-back, and bag redesign (Wagner, 2017). Currently, several federal bills have been proposed to address plastic pollution, such as Save Our Seas Act 2.0 (116 Congress, 2019), Plastic Waste Reduction and Recycling Act (116 Congress, 2020), and Break Free From Plastic Pollution Act (116 Congress, 2020). Despite these much-needed efforts (Iverson, 2019), little is known on how much plastic pollution can potentially be reduced in the U.S. by these bills and similar policies.

Knowing how much plastic pollution can be reduced depends on an understanding of how plastic production, consumption, and waste have historically evolved. A material flow analysis (MFA) helps characterize the metabolism of materials in a society through accounting and tracing material flows and stocks (Brunner and Rechberger, 2016). Studies have examined the material flows of plastics at the country level in a single year by using static MFA (Bureecam et al., 2018; Heller et al., 2020; Mutha et al., 2006). Although these static MFA studies clearly show a snapshot of the plastic life cycle in a society from production to end-of-life (EOL), they give little information on the in-use stock of plastic materials and historical trends of plastic flow. Therefore, a dynamic MFA is needed to characterize the long-term dynamics of plastic flow and stock (Chen and Graedel, 2012). Specifically, dynamic MFA has been used widely to model flows and stocks of various metals (Müller et al., 2014). Some studies also modeled the dynamic flows of a few particular polymers in Europe (Ciacci et al., 2017; Eriksen et al., 2020) and China (Liu et al., 2020). To the best of our knowledge, only Jiang et al. (2020) studied the dynamic flow and stock of plastics for a country (China). A detailed, long-term dynamic assessment of plastic flow and stock in the U.S. is still lacking.

In this study, I developed a dynamic MFA model for flows and stocks of nine commonly used plastic polymers in seven commodity sectors with five end-of-life pathways in the U.S. for almost seven decades (1950-2018). Based on the in-depth understanding of the historical dynamics of plastic flow and stock, I quantified the amount of plastic pollution, originating from landfilled waste and mismanaged waste, and evaluated future scenarios to explore pathways for the U.S. to achieve zero plastic pollution by 2050. I also assessed the potential of policies and actions that reduce plastic pollution to identify policy gaps and derive policy suggestions.

2. Methodology

2.1 Overall approach and system boundaries

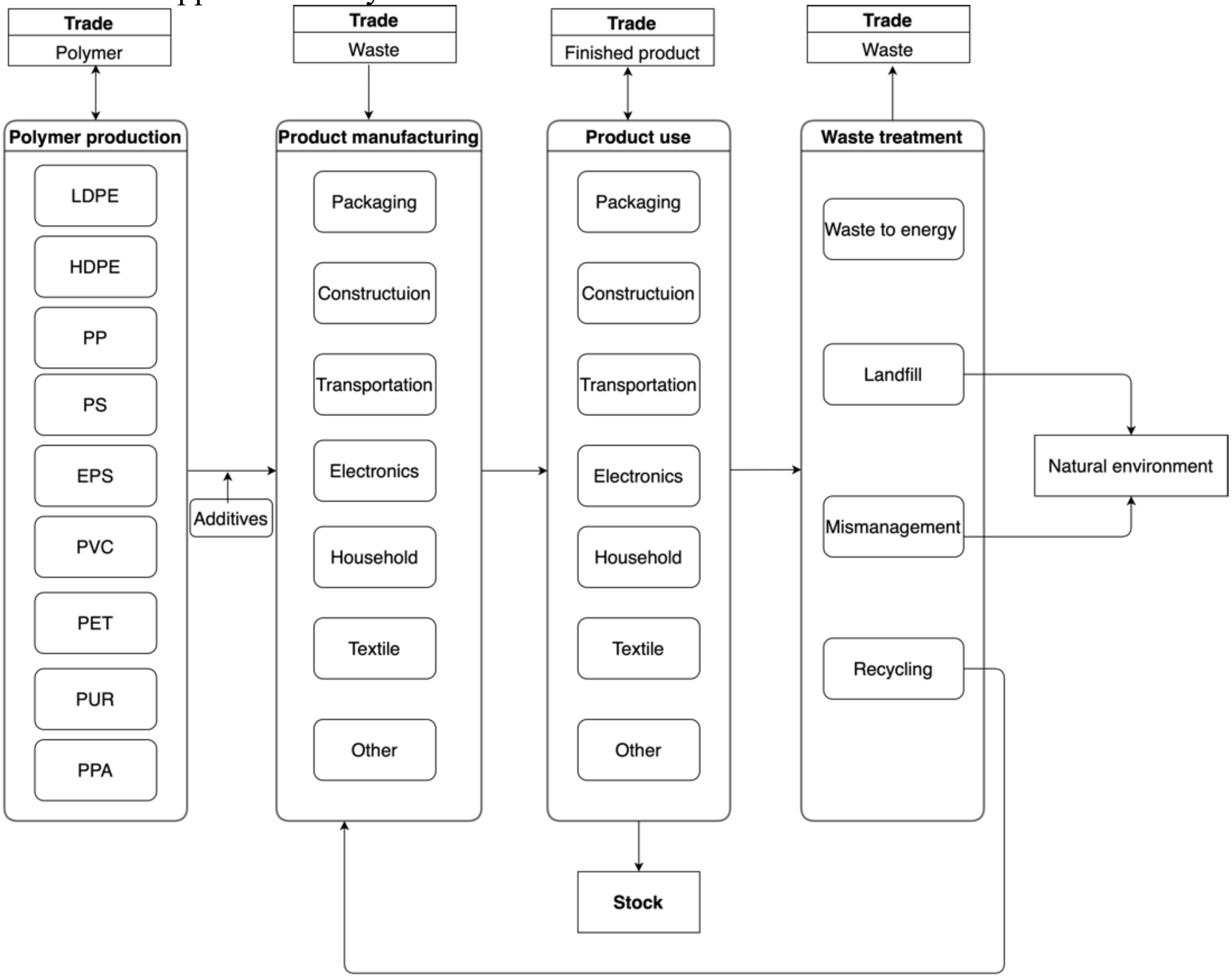

Figure 1. Framework of plastic stock and flow analysis in the United States. Boxes represent life cycle of plastics and arrows represent flows.

This study is conducted through two major modelling approaches: dynamic material flow analysis and scenario analysis. First, I developed a dynamic MFA model to assess plastic stock and flow in the U.S. The model covers the years 1950 – 2018, with a time interval of one year. The system boundary of this study is mapped in Figure 1. Specifically, I investigated the flow of the major nine major polymers in the U.S. market: low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), expandable polystyrene (EPS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR), and polyphthalamide (PPA). According to American Chemistry Council (2019), in 2018, the total consumption of LDPE, HDPE, PP, PS, EPS, and PVC was about 30 million metric tons, accounting for 55% of the U.S. plastic consumption. The quantities of PUR, PET, and PPA are estimated to be 3.3 million metric tons (ACC, 2020), 6.7 million metric tons (Kuczenski and Geyer, 2010), and 7.8 million metric tons (Geyer et al. 2017), respectively. Together, these nine polymer groups represent nearly 90% of annual plastic consumption in the United States. I believe that the assessment of these nine polymers would enhance our understanding of the flow and stock of the overall plastic industry in the U.S.

Second, I developed six scenarios to estimate the reduction in plastic pollution from 2019 – 2050 based on the changes in plastic bag policy, per capita plastic consumption, ratio of the different waste treatment pathways, and lifespans of various plastic products. The analysis is intended to identify the most effective strategy to combat plastic pollution in the U.S. and support environmental policy-making. The scenario descriptions are available in section 2.3.

2.2 Flows and stocks

To track the historical flow of plastics in almost seven decades, I quantified polymer production, international plastic trade, plastic consumption, and waste management and recovery. The calculations are available in the following subsections.

2.2.1 Polymer production

The polymer production data from 1979 to 2018 are obtained from American Chemistry Council (ACC, 2009; ACC, 2019), and the data from 1950 to 1978 are computed based on the global production data and breakdown of total production by country (Geyer et al., 2017). Depending on the use and polymer types, plastic contains different additives, such as heat stabilizers, fillers, plasticizers, and flame retardants (Babayemi et al., 2019). These additives are incorporated into polymers to strengthen their mechanical, physical, or chemical properties, to protect polymers from the degradation of light, heat, and bacteria, and to improve surface appearance (ACC, 2019). The average share of additives used in all polymers, except PPA, is estimated at around 8% (Geyer et al., 2017). The total plastic production is the sum of polymer and additive production and is described in equation 1:

$$P_{t_n} = (P_{LDPE,t_n} + P_{HDPE,t_n} + P_{PP,t_n} + P_{PS,t_n} + P_{EPS,t_n} + P_{PVC,t_n} + P_{PET,t_n} + P_{PUR,t_n}) \times 1.0828 + P_{PPA,t_n} \qquad (1)$$

where P_{t_n} is the production of all polymers at time t_n; P_{LDPE,t_n} is the production of LDPE at time t_n; P_{HDPE,t_n} is the production of HDPE at time t_n; P_{PP,t_n} is the production of PP at time t_n; P_{PS,t_n} is the production of PS at time t_n; P_{EPS,t_n} is the production of EPS at time t_n; P_{PVC,t_n} is the production of PVC at time t_n; P_{PET,t_n} is the production of PET at time t_n; P_{PUR,t_n} is the production of PUR at time t_n; P_{PPA,t_n} is the production of PPA at time t_n; Additives is 8.28% of the weight of polymers.

2.2.2 International trade

There are four types of trade occurring in the plastic life cycle: polymers, imported plastic waste for manufacturing, finished plastic products, and post-consumption plastic waste. I included the trade of polymers and formed plastics (tube, sheet, films, etc) based on data from the UN Comtrade database (United Nations, 2021). The categorization of formed plastics is available in supporting information (SI) Table S1. The database also provides trade history of PET, PS, PVC, and other plastic waste (designated in the database as "plastics waste or scrap nes"). Since the distribution of imported polymers and waste in each sector is unknown, I assumed it is consistent with the distribution of locally produced polymer in seven commodity sectors including packaging, construction, transportation, electronics (EE), households (HH), textile, and other.

2.2.3 Product consumption

The data about the share of total polymer production according to polymer type and commodity sectors are from Geyer et al. (2017). In this study, I assumed the share is constant throughout the modeling period of 1950 – 2018. This assumption is consistent with the most recent dynamic plastic flow analysis at the country level (Liu et al., 2020). The amount of product consumption is the sum of all locally produced polymers, net import of polymers, imported waste that is recycled to make new plastic products, recycled plastics from locally produced waste, and net import of finished products. Plastic flow into each commodity sector is calculated by equation 2.

$$C_{s,t_n} = \sum_{p=1}^{9}(P_{P,t_n} + NI_{P,t_n} + IW_{P,t_n}) * R_{p,s,t_n} + SP_{s,t_n} + NP_{s,t_n} \qquad (2)$$

where C_{s,t_n} is the consumption of plastic in sector s at time t_n. P_{P,t_n} is the production of polymer p at time t_n. NI_{P,t_n} is the net import of polymer p at time t_n. IW_{P,t_n} is imported polymer waste p at time t_n. R_{p,s,t_n} is product split ratio, representing ratio of polymer p flowing to sector s at time t_n. SP_{s,t_n} refers the recycled waste flow to sector s at time t_n and the calculation is given in equation 4. NP_{s,t_n} refers the net import of finished product flowing into sector s

2.2.4 Waste management and recovery

Lifespans determine how long plastic products last in the economy and when they become plastic waste (Murakami et al., 2010). Several studies have provided the estimation of plastic product lifespan in different commodity sectors in China (Liu et al., 2020), Germany (Patel et al., 1998), Europe (Ciacci et al., 2017), and worldwide (Geyer et al., 2017). Here, to quantify the plastic waste generated each year in the studied period, I used the lifespan data (see SI Table S2) presented by Geyer et al., (2017) for two reasons. First, the availability of plastic lifespan in each sector in the U.S. is limited and the data for other countries have great variations. Second, I followed Heller et al., (2020), who also used the data from Geyer et al., (2017) to conduct a static MFA study that focuses on the U.S. plastic flow in a single year. The quantity of plastic waste generated from the end-of-life of sector s in a particular year, FW_{s,t_n} is described as:

$$FW_{s,t_n} = \sum_{t_m=1}^{68} C_{s,t_n-t_m} \times L_{i,t_m} \qquad (3)$$

where C_{s,t_n-t_m} is the plastic in sector s that becomes waste in year $(t_n - t_m)$. L_{i,t_m} is calculated by using log-normal lifetime distribution models based on the log mean and log standard deviation of lifespans for seven end-use sectors.

Waste treatment has five pathways: mismanagement, recycling, waste-to-energy, landfill, and export. In this study, I assumed waste in construction, EE, and transportation sectors has distinct treatment ratios, while the waste from the remaining sectors has the same treatment ratio in each pathway. For decades, partial plastic waste in the recycling pathway has been exported to Asia, mainly in mainland China and Hong Kong (Wen et al., 2021). Brooks et al. (2018) estimated that 12.4% of global plastic waste export is from the U.S., the largest exporting country of plastic waste globally. Because partial plastic is exported, the final recyclable plastic waste within the country is the difference between the waste getting into the recycling pathway and the exported waste. The recyclable waste is recovered to manufacture new products. I assumed the recycled plastic gets back to the system in the year the waste is generated. I also assumed all plastics can be recycled only once; after the second use of plastics, all waste is landfilled, mismanaged, or combusted to generate energy. The recyclable waste generated from first-time consumption in each sector, and the inflow from recycled primary plastic waste to each sector for second time consumption are calculated by equation 4 and equation 5, respectively.

$R_{s,t_n} = FW_{s,t_n} \times RR_{s,t_n} - WE_{s,tn}$ (4)
where R_{s,t_n} is the recycled waste from each sector. FW_{s,t_n} is the waste produced from each sector. RR_{s,t_n} is the recycling ratio of each sector. $WE_{s,tn}$ is the exported waste to other countries.

$SP_{s,t_n} = \sum_{p=1}^{9} \sum_{s=1}^{7} R_{s,t_n} \times MS_{s,p,t_n} \times D_{si,sj}$ (5)
where MS_{s,p,t_n} represents the material share of each polymer in each sector. $R_{s,t_n} \times MS_{s,p,t_n}$ is used to quantify the recycled polymer in each sector. $D_{si,sj}$ refers the distribution of recycled polymer from sector s_i to s_j.

The calculation of secondary plastic waste is as same as the primary plastic waste and it is described in equation 6. The total waste in landfill, waste-to-energy, and mismanagement pathway is the sum in first-time waste management and second-time waste management. The calculation equations are below:

$SW_{s,t_n} = \sum_{t_m=1}^{68} SP_{s,t_n-t_m} \times L_{i,t_m}$ (6)
$LAN_n = \left(FW_{s,n} + SW_{s,t_n}\right) \times LL_{s,tn}$ (7)
$WTE_n = \left(FW_{s,n} + SW_{s,t_n}\right) \times WTE_{s,tn}$ (8)
$MIS_n = \left(FW_{s,n} + SW_{s,t_n}\right) \times MIS_{s,tn}$ (9)

where LAN_n is the total landfill waste; $LL_{s,tn}$ refers the landfill rate of waste from sector s at time t_n ; WTE_n is the total waste-to-energy plastics; $WTE_{s,tn}$ refers the waste-to-energy rate of waste from sector s at time t_n; MIS_n is the total mismanaged waste; $MIS_{s,tn}$ refers the mismanagement rate of waste from sector s at time t_n.

2.2.5 In-use stock

The in-use plastic stock refers plastics still in the active use status and provide services to society. The stock is calculated from lifespan and consumption of plastics products in different sectors, shown in equation 10. The lifespan of materials made from recycled plastic waste is assumed as the same as raw polymers. The total stock is stock from primary plastics consumption and secondary plastics consumption.

$S_{s,t_n} = \sum_{t_m=1}^{68} C_{s,t_n-t_m} \times (1 - L_{i,t_m}) + \sum_{t_m=1}^{68} R_{s,t_n-t_m} \times (1 - L_{i,t_m})$ (10)

where:

$1 - L_{i,t_m}$represents to stock span. $\sum_{t_m=1}^{68} C_{s,t_n-t_m} \times (1 - L_{i,t_m})$ calculates the stock accumulated from primary plastics consumption. $\sum_{t_m=1}^{68} R_{s,t_n-t_m} \times (1 - L_{i,t_m})$ calculates the stock accumulated from secondary plastics consumption.

2.3 Scenario analysis

Based on the dynamic MFA analysis, which shows the historical trend of plastic flows from 1950 to 2018, six prospective scenarios were evaluated to estimate potential reductions in plastic pollution from 2019 to 2050. These scenarios were created by three high-level categories of strategies: reduce, reuse, and recycling. The seven specific parameters considered in these scenarios are 1) adapting a national plastic grocery bag ban, 2) reducing plastic consumption, 3) improving the lifespan of plastic products, 4) increasing waste recycling rate, 5) abandoning waste export, 6) reducing mismanaged waste leakage, and 7) increasing waste incineration rate to utilize waste resources. As shown in Table 1, S1 represents the baseline situation; S2-4 assess the plastic pollution reduction potential through implementing a single initiative; and S5 and S6 are combined scenarios that evaluate the plastic pollution reduction potential through changing multiple parameters at the same time. The details for each scenario are described in the subsections below.

Scenario	**Single-use plastic bag**	**Plastic consumption**	**Lifespan**	**Recycling rate**	**Waste export rate**	**Mismanaged waste rate**	**Incineration rate**
S1: Business-as-usual (BAU)	No more plastic bag ban	Constant growth	Same as 2018	Same as 2018	Same as 2018	Same as 2018	Same as 2018
S2: Reduced consumption growth rate	Same as BAU	Since 2019, per capita plastic consumption remained at 0.24 metric tons/year (2018 per capita plastic consumption).	Same as BAU	Same as BAU	Same as BAU	Same as BAU	Same as BAU
S3: National Plastic bag ban	No single-use plastic bag from 2021[1]	Same as BAU	Same as BAU	Same as BAU	Same as BAU	Same as BAU	Same as BAU
S4: Increased lifespan	Same as BAU	Same as BAU	Increase lifespan to EU level.	Same as BAU	Same as BAU	Same as BAU	Same as BAU
S5: Ambitious	No single-use plastic bag from 2021.	Since 2019, per capita plastic consumption reduces by 20% than the BAU scenario[4].	Increase lifespan to EU level.	Increase plastic packaging recycling rate to 55% by 2030[2].	No plastic waste export from 2021[3].	No mismanaged plastic waste from 2019.	Same as BAU

S6: Target	No single-use plastic bag from 2021.	Since 2019, per capita plastic consumption became 0.044 metric tons per year[5].	Increase lifespan to EU level.	Increase all plastic waste recycling rate to 55% by 2030.	No plastic waste export from 2021.	No mismanaged plastic waste from 2019.	From 2030, all non-recycled waste will be incinerated to generate energy.

Table 1. Scenario Overview

[1] EU set a goal to ban single-use plastics by 2021.

[2] Consistent with EU recycling strategy

[3] Consistent with Norway's plastic waste export strategy

[4] Consistent with Dutch plastic consumption reduction plans

[5] World average per capita plastics consumption is 0.044 metric tons/per year (UN Environment Programme, 2018).

2.3.1 BAU

The BAU scenario provides a baseline of future plastic pollution and is used to compared with alternative intervention scenarios. This scenario assumes no more plastics policies will be implemented in the future. The rates of each waste management pathway and products' lifespan correspond to the conditions in 2018. I estimated that per capita plastic consumption will gradually increase from 0.24 metric tons in 2018 to 0.47 metric tons in 2050 (national plastic consumption will increase from 78,855 thousand metric tons in 2018 to 149,027 thousand metric tons in 2050) according to the predicted GDP (gross domestic product) in constant price data (OECD, 2020). I built a univariate regression model for GDP in constant price and historical per capita plastic consumption data from 1960 to 2018 in the U.S. The R square of the univariate regression is 0.9605, which means 96.05% of variations in per capita plastic consumption can be explained by GDP constant. More details about the regression model are available in Figure S1.

2.3.2 Scenario 2

From 1950 to 2018, per capita annual plastic consumption increased from 0.01 metric tons per year to 0.24 metric tons. To better understand the influence of plastics consumption on the total plastic pollution, this scenario assumes per capita plastic consumption from 2019 to 2050 will remain at 0.24 metric tons per year. As the predicted population is from 329 million in 2019 to 379 million in 2050 (United Nations, 2019), thus the total predicted consumption will increase from 79,330 thousand metric tons in 2019 to 91,469 thousand metric tons in 2050 (39% less than the total consumption in BAU scenario). All other parameters remain as same as in the BAU scenario.

2.3.3 Scenario 3

Currently, in the U.S., eight states have launched state-wide plastic grocery bag bans and many county governments have implemented similar plastic bag reduction actions (National Conference of State Legislature, 2021). However, to date, no national plastic bag ban exists in the U.S. Conversely, as of 2018, 35 countries have implemented bans on plastic bags and these cases have demonstrated success in reducing plastic consumption (Lam et al., 2018). This scenario aims to estimate the plastic pollution reduction potential through launching a national plastic grocery bag ban in the U.S. All statistics used for calculation are available in SI.

2.3.4 Scenario 4

This scenario evaluates the impact of increasing plastic lifespan on plastic pollution reduction. According to Ciacci et al. (2017), the lifespan of plastic products in the EU market is longer than that in the U.S. market. For example, the average lifetime of plastics in the construction sector in the EU and the U.S. are 50 years and 35 years, respectively. In this scenario, I scale up the U.S. plastic lifespan to the EU level. The modified lifespan parameters are available in Table S4.

2.3.5 Scenario 5

Scenario 5 assesses the effectiveness of combined individual initiatives. Specifically, I assumed the plastics grocery bag ban has been implemented, which is consistent with scenario 3; and the lifespan of plastic products increases to the EU level, which is consistent with scenario 4. The recycling rate for plastic packaging will increase to 55% by 2030 and it will keep growing steadily afterwards until the recycling rate reaches 100%. This scenario assumes no plastic waste export in the U.S. starting from 2021. This strategy is important because China, the largest importer of U.S. plastic waste announced to ban all plastic waste import beginning from 2020 (NDRC, 2020). In response to this policy, the U.S. has to increase the local waste management capacity to manage the waste that would otherwise ship to China. Researchers have suggested that improving the waste management infrastructure can remove the mismanaged plastic waste leakage to the natural environment (Jambeck et al., 2015). To consider the benefits from improved waste management infrastructure, this scenario assumes no mismanaged plastic waste leakage starting from 2019. Additionally, I assumed starting from 2019, annual per capita plastic consumption decreases by 20%, i.e., 1.92 metric tons, compared to the BAU scenario.

2.3.6 Scenario 6

This scenario aims to find the point when plastic pollution reaches 0 by 2050. On top of recycling strategies in scenario 4, I set a more ambitious recycling target; I assumed the recycling rate for all waste generated from all sectors will increase to 55% by 2030. It is founded that per capita plastic consumption in the U.S. is more than 3 times higher than the world average, ranged from 0.044 metric tons to 0.073 metric tons per year (UN Environment Programme, 2018; Alpizar, 2020). In this target scenario, I assumed from 2019, per capita plastic products reduce to 0.044 metric tons. Additionally, I assumed starting from 2030, all non-recycled waste will be incinerated to generated energy.

3. Results

3.1 Plastic flows

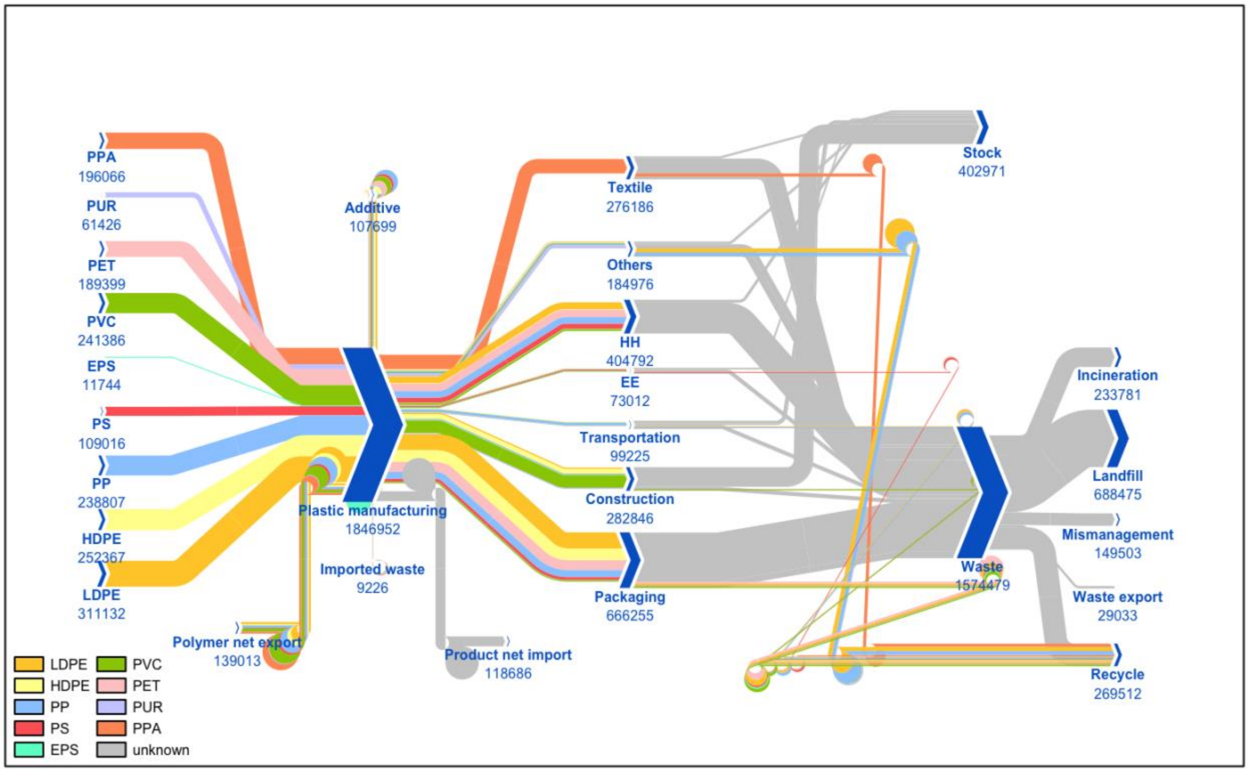

Figure 2. Aggregate model for the plastic cycle in the U.S. from 1950 – 2018. Colors and width of flows correspond to polymer types and mass, respectively. The units of the graph are in thousand metric tons.

Figure 2 shows aggregated plastic flows from polymer production to the end-of-life of plastics in the U.S. over the period 1950 to 2018. In almost seven decades, the U.S. produced 1,611,000 thousand metric tons of polymers. The largest contributor was LDPE, which shared about 19% of total production. The other five significant contributing polymers were HDPE (16% of total production), PVC (15%), PP (15%), PPA (12%) and PET (12%). The polymer production grew substantially in 68 years, reaching 58,000 thousand metric tons in 2018, 124 times more than the total production in 1950. The annual growth rate of polymer production was 7.4%.

There are three types of traded plastics between polymer production and plastic product consumption phase: polymers, polymer waste, and finished products. The U.S. started to trade polymers in 1962; the annual traded polymers increased from 2,300 thousand metric tons to 8,900 thousand metric tons in 2018. The cumulative net export of polymers was 139,000 thousand metric tons. The U.S. was a polymer export-only country prior to 1998. After that year, the U.S. started to import HDPE, EPS, and PET. Until 2018, the U.S. had imported 700 thousand metric tons of HDPE, 2,000 thousand metric tons of EPS, and 6,600 thousand metric tons of PET. In addition to the polymer trade, the U.S. also imported a small quantity of polymer waste, which was used for remanufacturing new plastics. Within 68 years, the U.S imported about 9,200 thousand metric tons of polymer waste. The third type of traded plastics is finished products. The U.S imported about 118,000 thousand metric tons of finished plastic products for consumption; the most imported plastics is in the textile sector (62,000 thousand metric tons), which accounts for more than half of total net plastic product import.

3.2 Plastic consumption

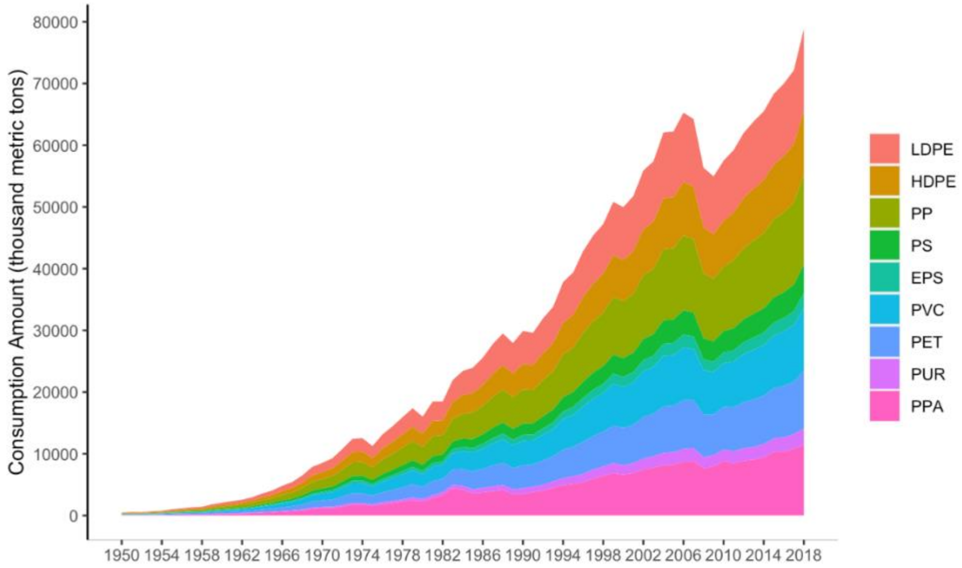

Figure 3. Consumption by polymer

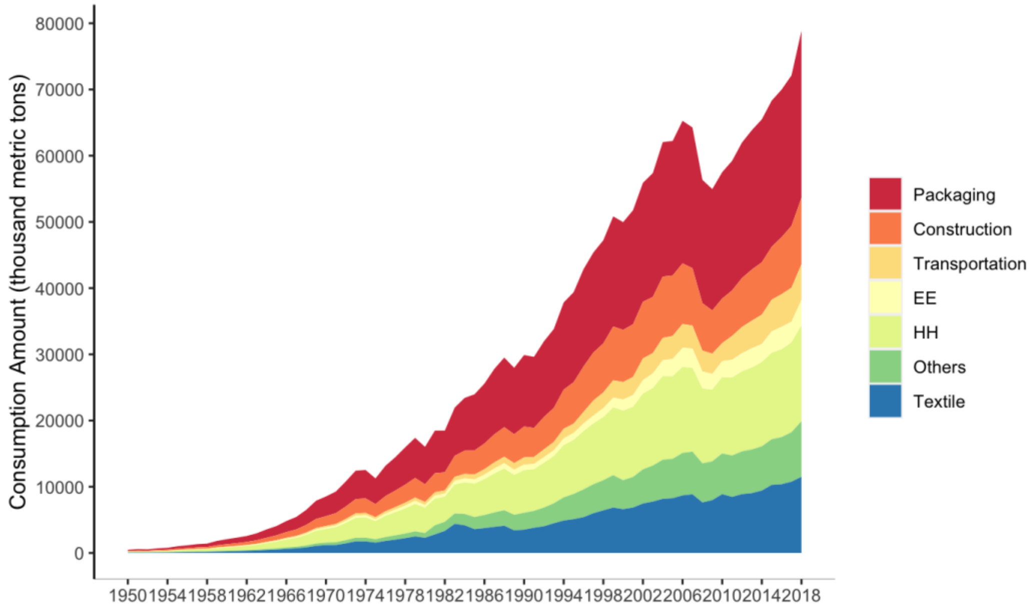

Figure 4. Consumption by commodity sector

Figure 3 shows the plastic consumption mass according to different polymer types. The total plastic consumption increased from 492 thousand metric tons in 1950 to 79,000 thousand metric tons in 2018. The aggregate plastic consumption over 68 years was 1,977,000 thousand metric tons. The most consumed polymer was PP, which reached 14,000 thousand metric tons in 2018. Another widely used plastic material was PE (LDPE and HDPE), which accounts for 30% of total consumption. Even though the consumption of both EPS and PUR increased by 8% annually, compared with other polymers, their quantities in 2018 were still low.

Figure 4 shows plastic consumption by commodity sectors. The packaging sector consumed the most plastics. It used 32% of total plastics in 2018 and 33.5% of cumulative plastics over the period 1950 to 2018. Other sectors that consumed a great number of plastics were household, construction, and textile. These sectors used 405,000 thousand metric tons (20.5% of cumulative consumption), 283,000 thousand metric tons (14.3%), and 276,000 thousand metric tons (14%) of plastics in almost seven decades, respectively. Although the consumption of the transportation sector increased steadily in an average growth rate of 9.6% from 1950, its cumulative consumption was only about 5% of total consumption.

3.3 In-use stocks

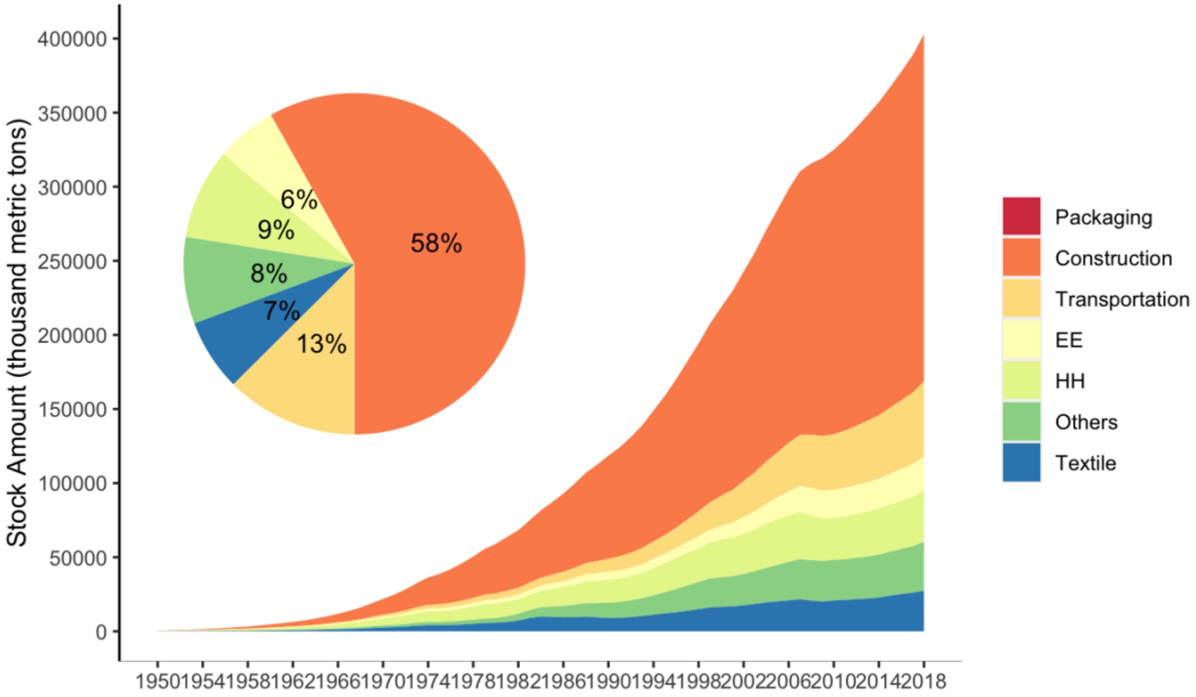

Figure 5. In-use stock by commodity sectors. The pie chart shows the distribution of in-use stock in seven sectors in 2018.

Figure 5 shows a growing trend of in-use plastic stock. The total stock increased from 315 thousand metric tons in 1950 to 403,000 thousand metric tons in 2018. By the end of that year, construction contained 234,000 thousand metric tons of stock, which accounted for 58% of total in-use stock from all sectors. Transportation also shared 13% of the in-use stock. The distribution of in-use stock in EE, HH, textile, and others were almost even. Plastic packaging has a short lifetime, most packaging gets into the waste management stage within one year, thus they rarely stay in the economy for continuous use.

3.4 Plastic recycling and waste management

Figure 6 shows waste by commodity sectors. The cumulative plastic waste from all sectors increased from 176 thousand metric tons in 1950 to 64,700 thousand metric tons in 2018, at a 9% annual growth rate. Different from the in-use stock, the packaging sector contributed the most to waste mass. Packaging's cumulative waste was 13 times more than the cumulative waste from the transportation, construction, and EE sectors. Compared with the consumption data, 99% of plastic packaging consumed over the period 1950 to 2018 were converted to waste by the end of 2018 and only a small amount of packaging consumption in 2018 still stays in the economy. At the end of 2018, 90% of consumption in HH and textile sectors was also moved into the waste management phase. On the contrary, because of the long lifespan of construction material, only 17% of construction plastics consumed in 68 years became waste at the end of 2018. The majority of the material is still in stock for use.

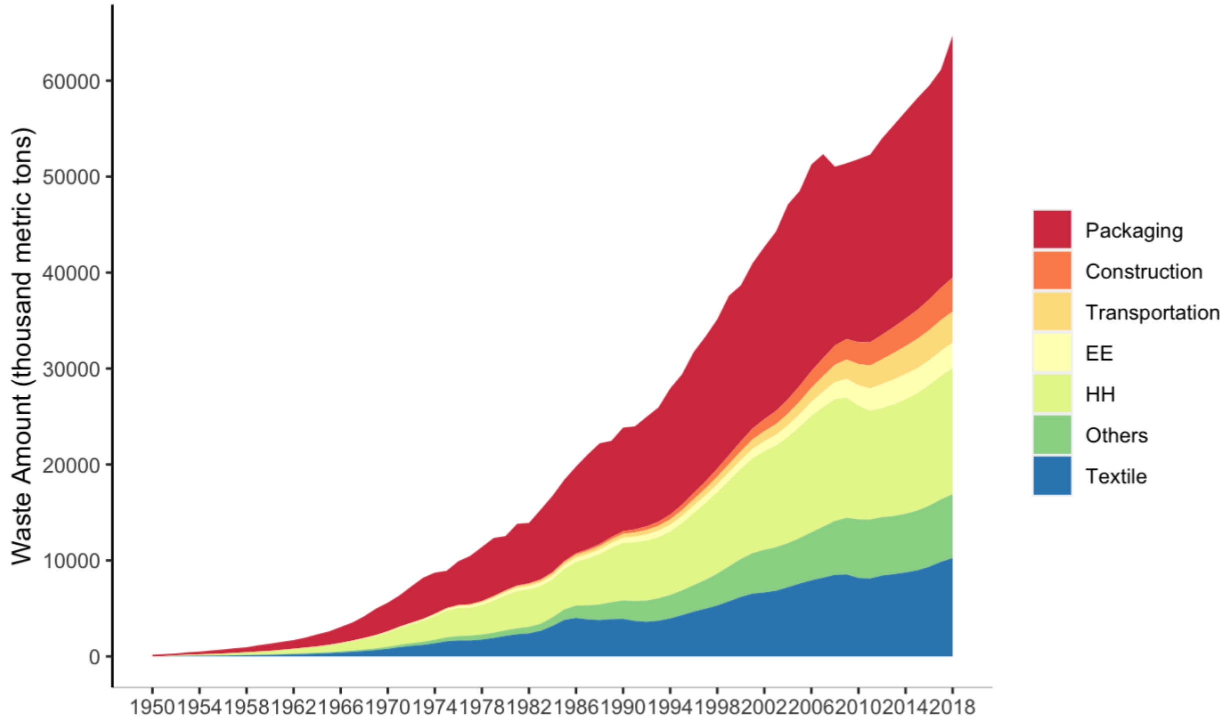

Figure 6. Waste by sector

Figure 7 shows the trend of end-of-life treatment for plastics in the U.S. within 68 years from 1950 to 2018. Colors distinguish each waste management pathway. Before 1980, almost all plastic waste was mismanaged; since then, plastic waste has been better managed. The U.S. started to ship plastic waste internationally in 1991. Through 2018, the U.S. has exported 29,000 thousand metric tons, more than three times higher than the imported waste, which suggests that the U.S. is a waste export country. The majority of waste that remained in the U.S. was incinerated, landfilled, or recycled. The incineration rate and recycling rate increased steadily, reaching 22% and 23% in 2018, respectively. It is worth noting that various sectors had very different end-of-life treatment pathways. The recycling rate in the transportation sector was always the highest and it reached 100% in 2012. The EE sector had the second highest recycling rate. In 2018, 39% of plastic waste from the EE sector was recycled to make new plastics. The recycling rate of the remaining sectors remained low; the majority of waste was landfilled.

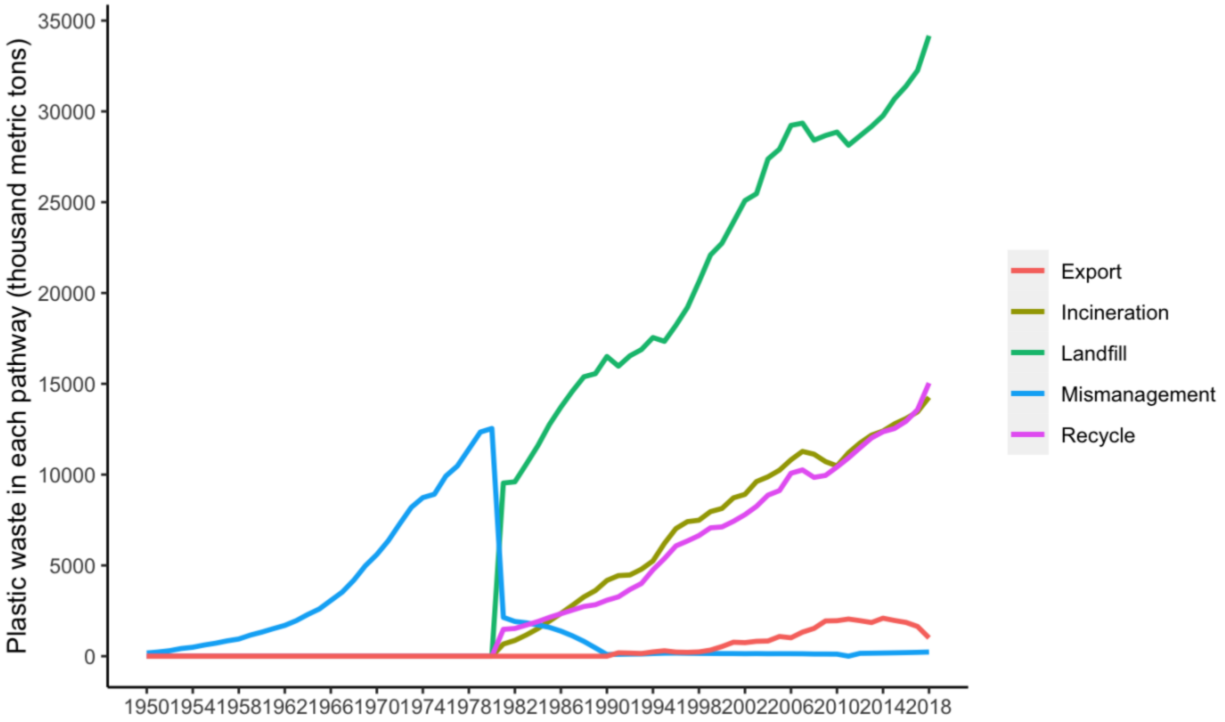

Figure 7. End-of-life treatment of plastics in the U.S. between 1950 and 2018

3.5 Scenario analysis

Figure 8 shows the historical and predicted plastics pollution mass under six scenarios. The solid line represents the historical plastic mass from 1950 to 2018, and the six dashed lines show the predicted plastic mass from 2019 to 2050 under the six scenarios. Scenario 1 is a business-as-usual scenario, which shows the trend of future plastic pollution mass if there were no more changes in the current system. As predicted, the plastic pollution mass would keep growing after 2019 and reach 67,000 metric tons in 2050. Scenario 2 suggests that keeping the per capita plastic consumption rate at the 2018 level could reduce plastic pollution after 2019. In 2050, plastic pollution would be 34% less than that under the BAU scenario. However, since the predicted population shows a growing trend, the total consumption of plastics would be growing as well, thus without changing other conditions in the system, the total plastics pollution would still increase. Under scenario 3, the predicted plastic pollution is lower than that under the BAU scenario. But the reduction is not that high because plastic grocery bags are responsible for 47% of packaging; the national plastic grocery bag ban does not affect the consumption of other packaging. Compared with scenario 3, the plastic pollution mass in scenario 4 is greater. It suggests that increasing plastic product lifespan could reduce plastic pollution, but that is not a very effective strategy.

Scenario 5 and scenario 6 are two combined scenarios which consider taking multiple initiatives at the same time. They show a greater reduction in plastic pollution than other scenarios which consider only one initiative. Taking scenario 5 for example, in 2050, the plastic pollution would be 68% less than plastic pollution under the BAU scenario. In scenario 6, the plastic pollution would be zero by 2050.

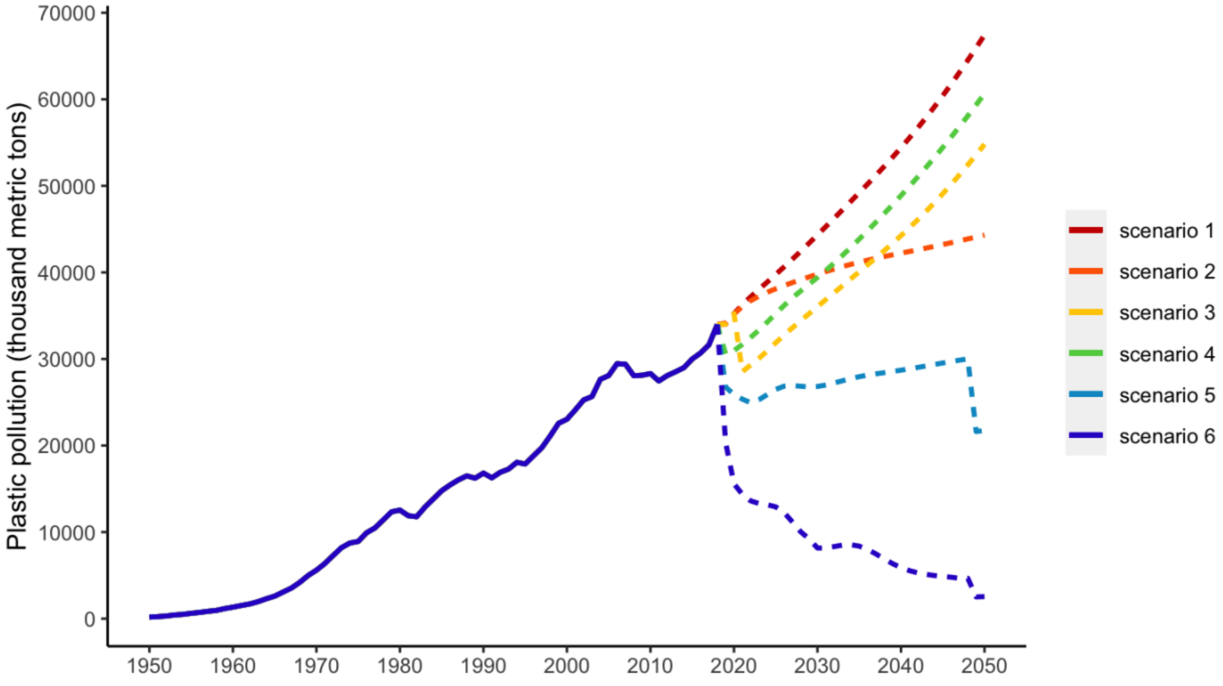

Figure 8. Plastic pollution (landfilled plastics and mismanaged plastics) from 1950 – 2050 under six scenarios

Scenario	Plastic pollution in 2050 (thousand metric tons)	Percentage of change
Scenario 1	67435	0%
Scenario 2	44306	-34%
Scenario 3	54806	-19%
Scenario 4	60648	-10%
Scenario 5	21740	-68%
Scenario 6	0	-100%

Table 2. Summary statistics of plastic pollution under six scenarios

4. Discussion

4.1 Trends and drivers of plastic pollution

From 1950 to 2018, the total plastic pollution in the U.S. has increased by 194 times. To assess the drivers of plastic pollution over 68 years, I used a PCWE identity – an adaption of the Kaya identity (Kaya, 1990) used for fossil fuel carbon dioxide emissions and Pale identity (Hong et al., 2021) used for land-use emissions.

$$E = P(\frac{C}{P})(\frac{W}{C})(\frac{E}{W}) = \mathrm{PCWE}$$

where E is the plastic pollution, P is population, C is plastic consumption, W is plastic waste; $\frac{C}{P}$ (c) represents per capita plastic consumption; $\frac{W}{C}$ (w) represents waste generation intensity from plastic consumption; $\frac{E}{W}$ (e) represents plastic pollution generation intensity from plastic waste.

The surge in plastic pollution was driven by the substantial growth in plastic consumption. According to Figure 9, between 1950 and 2018, per capita plastic consumption (c) has increased by 76 times, reflecting the growing use of plastics in the economy. In contrast with plastic pollution and per capita plastic consumption, population and waste generation intensity from consumption grew much slower. From 1950 to 2018, they have increased by 128% and 105%, respectively. This indicates that they are not significant drivers of plastic pollution. Plastic pollution generation intensity (e) from plastic waste shows a downward trend, meaning the portion of waste that became pollution has decreased. This is because of the growth in the recycling rate and incineration rate. Prior to 1980, all plastic waste was mismanaged, which turned into plastic pollution. Since then, waste management pathways have become more diverse. Partial plastic waste that had been mismanaged started to get recycled to manufacture new materials or incinerated to generate energy. As a result, the plastic pollution generation intensity (e) started to decrease after 1980.

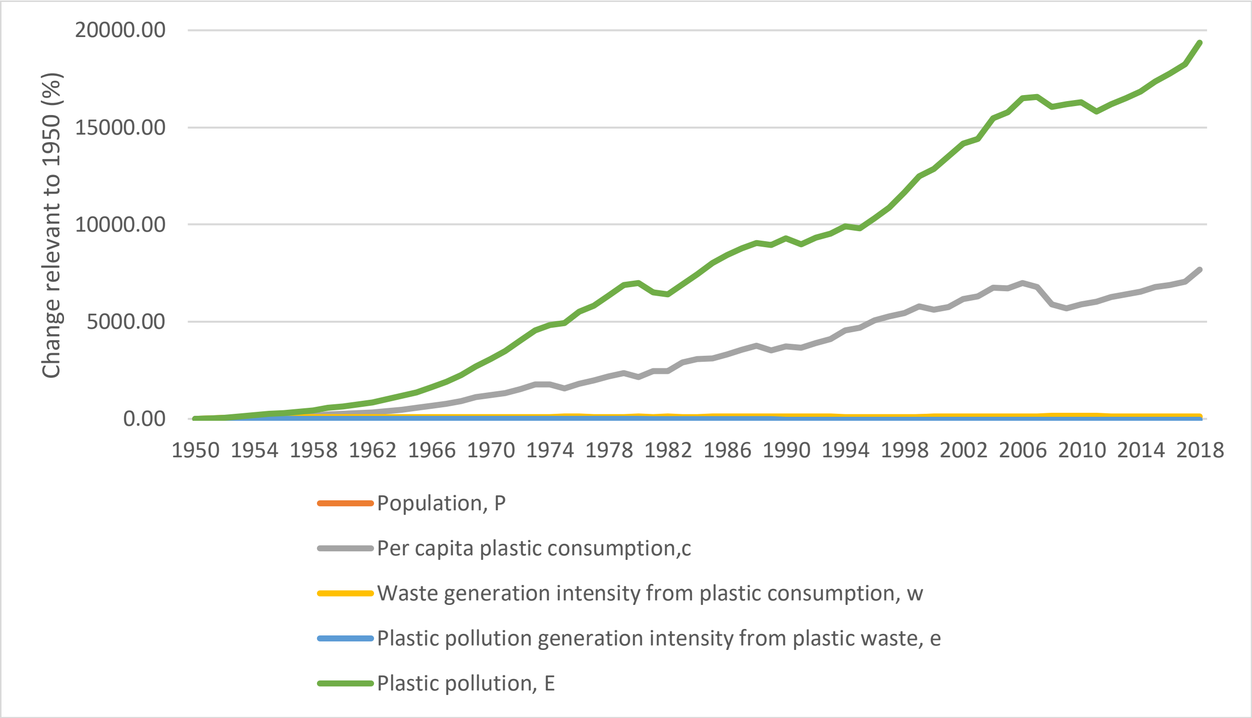

Figure 9. Trend and drivers of plastic pollution from 1950 to 2018.

4.2 Effectiveness of plastic bag ban

The most common strategy to combat plastic pollution taken in the U.S. is to implement a plastic bag ban to restrict the consumption of plastic grocery bags and encourage people to use plastic alternatives. Even though no national plastic bag ban exists in the United States, eight states including California, Connecticut, Delaware, Hawaii, Maine, New York, Oregon, and Vermont, and five cities including Boston, Chicago, Los Angeles, San Francisco, and Seattle have banned single-use plastic bags ((National Conference of State Legislature, 2021). However, this study suggests even if the U.S. implements a national plastic bag ban in 2021, it would not reduce plastic pollution substantially. This is because plastic bags only account for 47% of packaging, or 16% of total plastic consumption. Phasing out plastic bag consumption does not affect the consumption of the majority of plastics used for other purposes. Therefore, implementing a national plastic bag ban is not sufficient for the U.S. to achieve zero plastic pollution.

4.3 Policy suggestions

4.3.1 Set recycling targets

Increasing plastic recycling is one of the most effective approaches to reduce plastic waste pollution for two reasons. First, it could reduce plastics that go to landfill and mismanagement pathways. Second, materials recycled from plastic waste could be used to substitute new plastics.

By 2018, all plastic waste from the transportation sector achieved full recycling. However, the recycling rate in other sectors was low. Specifically, 38% and 22% of waste from EE and construction was recycled in 2018, respectively. From 1981 to 2018, the recycling rate of packaging, household, textile, and other sectors increased from 11% to 26%, with a 2% annual increasing rate. Following the current recycling growth rate, by 2030, the recycling rate for packaging, household, textile, and other sectors will be 33%, far less than 55%, the target recycling rate for the U.S. to achieve zero plastic pollution. Currently, the U.S. has not set any plastic recycling targets, while many developed countries have set ambitious recycling targets for either a particular sector or general plastic waste. For example, the European Commission (2019) aims to recycle at least 55% of all plastic packaging by 2030. Australia, Portugal, and the Netherlands have set a goal to recycle 70% plastic packaging by 2025 (Australian Government, 2018; Ellen Macarthur Foundation, 2020; Government of the Netherlands, 2020). Germany aims to increase its plastic recycling targets to 63% by 2022 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2017). And Korea aims to achieve a 70% plastic recycling goal by 2030 (Ministry of Environment, 2018).

4.3.2 Improve the management of landfilled waste

Landfill is the most common plastic treatment pathway undertaken by the U.S. In 2018, more than 34,000 thousand metric tons of waste was landfilled, which was greater than the total plastic waste that was recycled and incinerated. Landfilled waste has a long-term negative impact on the natural environment. Greenhouse gases such as carbon dioxide and methane are released to air when landfilled plastic waste decomposes. Also, after the degradation of plastic waste, polymer additives can percolate into environment, and then cause soil and water contamination (Alabi et al., 2019). Therefore, to achieve the zero plastic pollution target, more attention should be given to the landfilled waste reduction. Currently, a lot of plastic waste is collected and disposed with other types of waste; thus some plastics are contaminated with food and other materials, making it hard for recycling. This suggests there is a need to have a better waste sorting system to separate plastic from other types of waste. Case studies have proven implementing a better waste sorting system can reduce mixed waste getting into the landfill pathway. For example, in July 2019, a metro city in China - Shanghai enforced a standard for the classification of separated waste. Two months later after the standard got issued, the daily recycled waste increased by 5-fold compared to 2018, and the amount of ‘black’ waste, which includes different types of waste decreased by 26% (Lee et al, 2020).

5. Conclusions

This study used dynamic MFA to assess the flow and stock of plastics in the U.S. for almost seven decades (1950-2018). The polymer production grew substantially in 68 years, reaching 58,000 metric tons in 2018, 124 times more than the total production in 1950. The total plastic consumption increased from 492 thousand metric tons in 1950 to 79,000 thousand metric tons in 2018. The difference between plastic production and plastic consumption was attributed to international plastic trade and recovered material from plastic waste. The plastic waste increased from 176 thousand metric tons in 1950 to 64,700 thousand metric tons in 2018, at a 9% annual growth rate. As plastic products in different commodity sectors have varying lifespans, the contribution from each sector to plastic waste and in-use stock was different. For example, the packaging sector contributed the most to waste mass because almost all packaging materials became waste in the year they are consumed. Plastics in the construction sector contributed the least to waste because they have a much longer lifespan than other sectors, the majority of plastic products in construction sectors produced by 2018 is still in stock for use. Before 1980, almost all plastic waste was mismanaged; since then, plastic waste has been better managed as the occurring of four more waste management pathways such as recycling, waste-to-energy, incineration, and international waste export. The incineration rate and recycling rate increased steadily, reaching 22% and 23% in 2018, respectively. The majority of the remaining plastic waste was landfilled.

This study also evaluated six scenarios to explore pathways for the U.S. to achieve zero plastic pollution by 2050 through changing plastic bag policy, per capita plastic consumption, ratio of the different waste treatment pathways, and lifespans of various plastic products. I found that reducing per capita consumption is an effective strategy to combat plastic pollution. Statistically speaking, keeping the per capita plastic consumption rate at the 2018 level would make plastic pollution in 2050 34% less than the BAU scenario. Although implementing a national plastic bag ban and increasing plastic product lifespan are also able to reduce plastic pollution by 18% and 10%, respectively, it is impossible for the U.S. to achieve the zero plastic pollution target by 2050 through implementing an individual strategy. Thus, a more ambitious combined initiative that taking actions in different aspects at the same time is needed. I found that through 1) implementing a national plastic bag ban from 2021, 2) reducing annual per capita plastic consumption to world average level (0.44 metric tons), 3) increasing lifespan to EU level, 4) increasing all plastic waste recycling rate to 55% by 2030, 5) removing plastic waste export from 2021, 6) removing mismanaged plastic waste from 2019, and 7) substituting landfill by waste-to-energy to manage all non-recycled waste can help the U.S. to achieve the goal.

This study is the first dynamic MFA study to track the U.S. plastic flow over a time frame. It is helpful to improve our understanding of the dynamics of plastics in the U.S. and to inform strategies to combat the plastic pollution issue. However, this study presents some limitations. First, I used the lifespan data presented by Geyer et al. (2017), which assumes the lifespan of products in each sector is constant over seven decades. Because the lifespan of products is influenced by the availability of plastic alternatives and available technologies that can improve the durability of plastics, I believe the lifespan would likely be changing if this study consider these two factors. Second, as the data for the yearly distribution of polymers across seven commodity sectors is limited, I assumed the distribution remains the same from 1950 to 2018. I acknowledge that the distribution of polymer in each sector very likely has shifted over years. Future studies should consider a dynamic lifespan and a dynamic distribution of polymer across commodity sectors.

References

Alabi OA, Ologbonjaye KI, Awosolu O, Alalade OE (2019) Public and Environmental Health Effects of Plastic Wastes Disposal: A Review. J Toxicol Risk Assess 5:021. doi.org/10.23937/2572-4061.1510021

Alpizar, F, Carlsson, F, Lanza, G, Carney, B, Daniels, R.C, Jaime, M, Ho, T, et al. (2020). A framework for selecting and designing policies to reduce marine plastic pollution in developing countries. *Environmental science & policy,* 109(July 2020), 25–35. Elsevier Ltd.

American Chemistry Council (ACC). (2019). 2019 Resin Review: the Annual Statistical Report of the North American Plastics Industry

American Chemistry Council (ACC). (2020). The Economic Benefits of the U.S. Polyurethanes Industry 2019

Auatralian Government Department of Agriculture, water and the Environment. (2018). Australia's 2025 National Packaging Targets. https://www.environment.gov.au/protection/waste/plastics-and-packaging/packaging-covenant

Barnes, D.K.A, Morley, S.A, Bell, J, Brewin, P, Brigden, K, Collins, M, Glass, T, et al. (2018). Marine plastics threaten giant Atlantic Marine Protected Areas. Current biology, 28(19), R1137–R1138. Letter, England: Elsevier Ltd.

Babayemi, Joshua O, Nnorom, Innocent C, Osibanjo, Oladele, & Weber, Roland. (2019). Ensuring sustainability in plastics use in Africa: consumption, waste generation, and projections. *Environmental sciences Europe*, 31(1), 1–20. Berlin/Heidelberg: Springer Berlin Heidelberg.

Brunner, Paul H, & Rechberger, Helmut. (2016). Practical handbook of material flow analysis.

Brooks, Amy L, Wang, Shunli, & Jambeck, Jenna R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Science advances*, *4*(6), eaat0131. Research Support, Non-U.S. Gov't, United States.

Bureecam, Chira, Chaisomphob, Taweep, & Sungsomboon, Praj-Ya. (2018). Material flows analysis of plastic in Thailand. *Thermal science*, 22(6 Part A), 2379–2388. Belgrade: Society of Thermal Engineers of Serbia.

Chae, Yooeun, & An, Youn-Joo. (2018). Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. *Environmental pollution* (1987), 240, 387–395. Journal Article, England: Elsevier Ltd.

Chen, Wei-Qiang, & Graedel, T. E. (2012). Anthropogenic Cycles of the Elements: A Critical Review. *Environmental science & technology*, 46(16), 8574–8586. Journal Article, Washington, DC: American Chemical Society.

Ciacci, L, Passarini, F, & Vassura, I. (2017). The European PVC cycle: In-use stock and flows. *Resources, conservation and recycling*, 123, 108–116. Elsevier B.V.

Posen, I Daniel, Jaramillo, Paulina, Landis, Amy E, & Griffin, W Michael. (2016). Greenhouse gas mitigation for U.S. plastics production: energy first, feedstocks later. *Environmental research letters*, 12(3), 34024. IOP Publishing.

Eriksen, Marie Kampmann, Pivnenko, Kostyantyn, Faraca, Giorgia, Boldrin, Alessio, & Astrup, Thomas Fruergaard. (2020). Dynamic Material Flow Analysis of PET, PE, and PP Flows in Europe: Evaluation of the Potential for Circular Economy. *Environmental science &*

technology, *54*(24), 16166–16175. Journal Article, United States: American Chemical Society.

European Commission. (2019). Single-use plastics. https://ec.europa.eu/environment/topics/plastics/single-use-plastics_en#ecl-inpage-840

Ellen Macarthur Foundation.(2020) Portugal joins the Plastics Pact network. https://www.newplasticseconomy.org/news/portugal-joins-the-plastics-pact-network

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. (2017). New packaging law passes the Federal Council. https://www.bmu.de/pressemitteilung/neues-verpackungsgesetz-passiert-den-bundesrat/

Geyer, Roland, Jambeck, Jenna R, & Law, Kara Lavender. (2017). Production, use, and fate of all plastics ever made. *Science advances,* 3(7), e1700782. Research Support, U.S. Gov't, Non-P.H.S, United States.

Government of the Netherlands. (2020) State Secretary Van Veldhoven launches new campaign to combat packaging waste. https://www.government.nl/latest/news/2020/07/03/state-secretary-van-veldhoven-launches-new-campaign-to-combat-packaging-waste

Heller, Martin C, Mazor, Michael H, & Keoleian, Gregory A. (2020). Plastics in the US: toward a material flow characterization of production, markets and end of life. *Environmental research letters,* 15(9), 94034. IOP Publishing.

Jefferson Hopewell, Robert Dvorak, & Edward Kosior. (2009). Plastics recycling: challenges and opportunities. Philosophical transactions. *Biological sciences,* 364(1526), 2115–2126. Journal Article, England: The Royal Society.

Hong, Chaopeng, Burney, Jennifer A, Pongratz, Julia, Nabel, Julia E M S, Mueller, Nathaniel D, Jackson, Robert B, & Davis, Steven J. (2021). Global and regional drivers of land-use emissions in 1961-2017. *Nature* (London), 589(7843), 554–561. Historical Article, England: Nature Publishing Group.

Iverson, Autumn R. (2019). The United States requires effective federal policy to reduce marine plastic pollution. *Conservation science and practice,* 1(6), e45-n/a. article, Chichester, UK: John Wiley & Sons, Ltd.

Jiang, Xiaobin, Wang, Tao, Jiang, Meng, Xu, Ming, Yu, Yadong, Guo, Baohua, Chen, Dingjiang, et al. (2020). Assessment of Plastic Stocks and Flows in China: 1978-2017. *Resources, conservation and recycling,* 161, 104969. Elsevier B.V.

Jenna R. Jambeck, Roland Geyer, Chris Wilcox, Theodore R. Siegler, Miriam Perryman, Anthony Andrady, Ramani Narayan, et al. (2015). Plastic waste inputs from land into the ocean. *Science (American Association for the Advancement of Science),* 347(6223), 768–771. American Association for the Advancement of Science.

Kuczenski, Brandon, & Geyer, Roland. (2010). Material flow analysis of polyethylene terephthalate in the US, 1996–2007. *Resources, conservation and recycling*, *54*(12), 1161–1169. Kidlington: Elsevier B.V.

Kaya, Y., 1990. Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios. Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris.

Lam, Chung-Sum, Ramanathan, Soundaram, Carbery, Maddison, Gray, Kelsey, Vanka, Kanth Swaroop, Maurin, Cristelle, Bush, Richard, et al. (2018). A Comprehensive Analysis of Plastics and Microplastic Legislation Worldwide. *Water, air, and soil pollution*, *229*(11), 1–19. Cham: Springer International Publishing.

Liu, Yijie, Zhou, Chuanbin, Li, Feng, Liu, Hongju, & Yang, Jianxin. (2020). Stocks and flows of polyvinyl chloride (PVC) in China: 1980-2050. *Resources, conservation and recycling,* 154, 104584. Elsevier B.V.

Lowenthal, A. S. (2020). H.R.5845 — 116th Congress (2019-2020): Break Free From Plastic Pollution Act of 2020. Congress.gov. https://www.congress.gov/bill/116th-congress/house bill/5845

Ministry of Environment. (2018) Goals and Measures. Retrieved from http://eng.me.go.kr/eng/web/index.do?menuId=466

National Conference of State Legislatures. (2021). State Plastic Bag Legislation. https://www.ncsl.org/research/environment-and-natural-resources/plastic-bag-legislation.aspx

National Development and Refirm Commission People's Republic of China (2020). https://www.ndrc.gov.cn/xxgk/zcfb/tz/202001/t20200119_1219275.html

Law, K. L., Starr, N., Siegler, T. R., Jambeck, J. R., Mallos, N. J., & Leonard, G. H. (2020). *The United States ' contribution of plastic waste to land and ocean*. *October*, 1–8.

Morten W. Ryberg, Alexis Laurent, M. H. (2018). Mapping of global plastics value chain and plastics losses to the environment (with a particular focus on marine environment). *UN Environment Programme*, 1–99.

Moore, C. (2020, October 15). *Plastic pollution*. *Encyclopedia Britannica*. https://www.britannica.com/science/plastic-pollution

Müller, Esther, Hilty, Lorenz M, Widmer, Rolf, Schluep, Mathias, & Faulstich, Martin. (2014). Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environmental science & technology,* 48(4), 2102–2113. Research Support, Non-U.S. Gov't, Washington, DC: American Chemical Society.

Murakami, Shinsuke, Oguchi, Masahiro, Tasaki, Tomohiro, Daigo, Ichiro, & Hashimoto, Seiji. (2010). Lifespan of Commodities, Part I : The Creation of a Database and Its Review. *Journal of industrial ecology,* 14(4), 598–612.

Mutha, Nitin H, Patel, Martin, & Premnath, V. (2006). Plastics materials flow analysis for India. *Resources, conservation and recycling,* 47(3), 222–244. Amsterdam: Elsevier B.V.

OECD.Stat. (2020). Gross domestic product (GDP) : GDP in US dollars, constant prices and PPPs. https://stats.oecd.org/index.aspx?queryid=61429

Patel, M.K, Jochem, E, Radgen, P, & Worrell, E. (1998). Plastics streams in Germany—an analysis of production, consumption and waste generation. *Resources, conservation and recycling,* 24(3), 191–215. Amsterdam: Elsevier B.V.

Roh Pin Lee, Bernd Meyer, Qiuliang Huang, Raoul Voss, Sustainable waste management for zero waste cities in China: potential, challenges and opportunities, *Clean Energy*, Volume 4, Issue 3, September 2020, Pages 169–201, https://doi.org/10.1093/ce/zkaa013

Sullivan, D. (2020). *S.1982 - 116th Congress (2019-2020): Save Our Seas 2.0 Act*. Congress.gov. https://www.congress.gov/bill/116th-congress/senate-bill/1982.

Stevens, H. M. (2020). H.R.7228 - 116th Congress (2019-2020): *Plastic Waste Reduction and Recycling Act*. Congress.gov. https://www.congress.gov/bill/116th-congress/house bill/7228?s=1&r=83

U.S. Census Bureau (2020). Number of households in the U.S. from 1960 to 2020. https://www.census.gov/quickfacts/fact/table/US/HCN010212

United Nations Environment Programme (2018). Mapping of global plastics value chain and plastics losses to the environment (with a particular focus on marine environment). Ryberg, M., Laurent, A., Hauschild, M. United Nations Environment Programme. Nairobi, Kenya.

Wagner, Martin, & Lambert, Scott. (2018). Freshwater Microplastics : Emerging Environmental Contaminants? The Handbook of Environmental Chemistry. Cham: Springer Open.

Wagner, Travis P. (2017). Reducing single-use plastic shopping bags in the USA. *Waste management (Elmsford),* 70, 3–12. Journal Article, United States: Elsevier Ltd.

Wen, Zongguo, Xie, Yiling, Chen, Muhan, & Dinga, Christian Doh. (2021). China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. *Nature communications*, *12*(1), 425. Research Support, Non-U.S. Gov't, England: Nature Publishing Group.

United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019, Online Edition. Rev. 1.

United Nations. (2021). Commodity Trade Statistics Database. http://data.un.org/browse.aspx?d=ComTrade

Supporting Information

Table S1. Categorization of formed plastics

Monofilament(>1mm), rods, etc, ethylene polymers	Other
Monofilament(>1mm), rods, etc, vinyl-chloride polymer	Other
Monofilament(>1mm), rods,not ethylene or vinyl polyme	Other
Sausage casings of hardened protein, cellulose	Other
Tube, pipe or hose, rigid, of polyethylene	Household
Tube, pipe or hose, rigid, of polypropylene	Household
Tube, pipe or hose, rigid, of polyvinyl chloride	Household
Plastic tube, pipe or hose, rigid, nes	Household
Plastic tube, pipe or hose, flexible, mbp > 27.6 MPa	Household
Flexible plastic tube/hose not reinforced, no fitting	Household
Flexible plastic tube/hose with fitting not reinforce	Household
Plastic tube, pipe or hose, flexible, nes	Household
Fittings for plastic tube, pipe or hose	Household
Floor, wall, ceiling cover, roll, tile, vinyl chlorid	Household
Floor/wall/ceiling cover, roll/tile not vinyl chlorid	Household
Self-adhesive plastic, rolls <20cm wide	Other
Self-adhesive plates, sheets, film, plastic, w >20 cm	Other
Sheet/film not cellular/reinf polymers of ethylene	Packaging
Sheet/film not cellular/reinf polymers of propylene	Packaging
Sheet/film not cellular/reinf polymers of styrene	Packaging
Sheet/film not cellular/reinf flexible vinyl polymer	Packaging
Sheet/film not cellular/reinf polymethyl methacrylate	Packaging
Sheet/film not cellular/reinf acrylic polymers nes	Packaging
Sheet/film not cellular/reinf polycarbonates	Packaging
Sheet/film not cellular/reinf polyethylene terephthal	Packaging
Sheet/film not cellular/reinf unsaturated polyesters	Packaging
Sheet/film not cellular/reinf polyesters nes	Packaging
Sheet/film not cellular/reinf regenerated cellulose	Packaging
Sheet/film not cellular/reinf cellulose acetate	Packaging
Sheet/film not cellular/reinf cellulose derivs nes	Packaging
Sheet/film not cellular/reinf polyvinyl butyral	Packaging
Sheet/film not cellular/reinf polyamides	Packaging
Sheet/film not cellular/reinf amino-resins	Packaging
Sheet/film not cellular/reinf phenolic resins	Packaging

Sheet/film not cellular/reinf plastics nes	Packaging
Sheet etc, cellular of polymers of styrene	Packaging
Sheet etc, cellular of polymers of vinyl chloride	Packaging
Sheet etc, cellular of polyurethane	Packaging
Sheet etc, cellular of regenerated cellulose	Packaging
Sheet etc, cellular of plastics nes	Packaging
Plastic sheet, film, foil or strip, nes	Packaging
Baths, shower-baths and wash basins, of plastics	Construction
Lavatory seats and covers of plastics	Construction
Bathroom wares nes, of plastics	Construction
Boxes, cases, crates etc. of plastic	Packaging
Sacks & bags (including cones) of polymers of ethylen	Packaging
Plastic sacks, bags, cone except of ethylene polymers	Packaging
Plastic carboys, bottles and flasks, etc	Packaging
Plastic spools, cops, bobbins and similar supports	Packaging
Plastic stoppers, lids, caps and other closures	Packaging
Plastic articles for goods conveyance or packing nes	Packaging
Plastic table and kitchen ware	Household
Plastic household, toilet articles not table, kitchen	Household
Plastic reservoirs, tanks, vats, etc, capacity <300l	Household
Plastic doors and windows and frames thereof	Household
Plastic shutters and blinds (including Venetian)	Household
Plastic builders' ware nes	Household
Plastic office and school articles and supplies	Other
Plastic apparel and clothing accessories	Textile
Plastic fittings for furniture, coachwork, etc	Household
Plastic statuettes and other ornamental articles	Household
Plastic articles nes	Other

Table S2. Summary of product lifetime (log-normal) distribution parameters

Parameters	Lifetime (Years)					ln(Mean/Sqrt(1+Var/SD^2))	Sqrt(ln((1+Var/Mean^2)
	Min	Max	Mean	Standard Deviation	Variance	μ	σ
Transport	1	20	13	3	9	2.53900694	0.22778243
Packaging	0	1	0.5	0.1	0.01	-0.712757537	0.1980422

Construction	10	60	35	7	49	3.535737705	0.1980422
Electrical and Electronic Applications	1	10	8	2	4	2.049129231	0.246220677
Household	1	10	3	1	1	1.045932031	0.324592846
Textile	5	30	20	3	9	2.984606969	0.14916638
Others	1	10	5	1.5	2.25	1.566349064	0.293560379

Figure S1. Linear regress model for GDP constant and per capita plastic consumption in the U.S

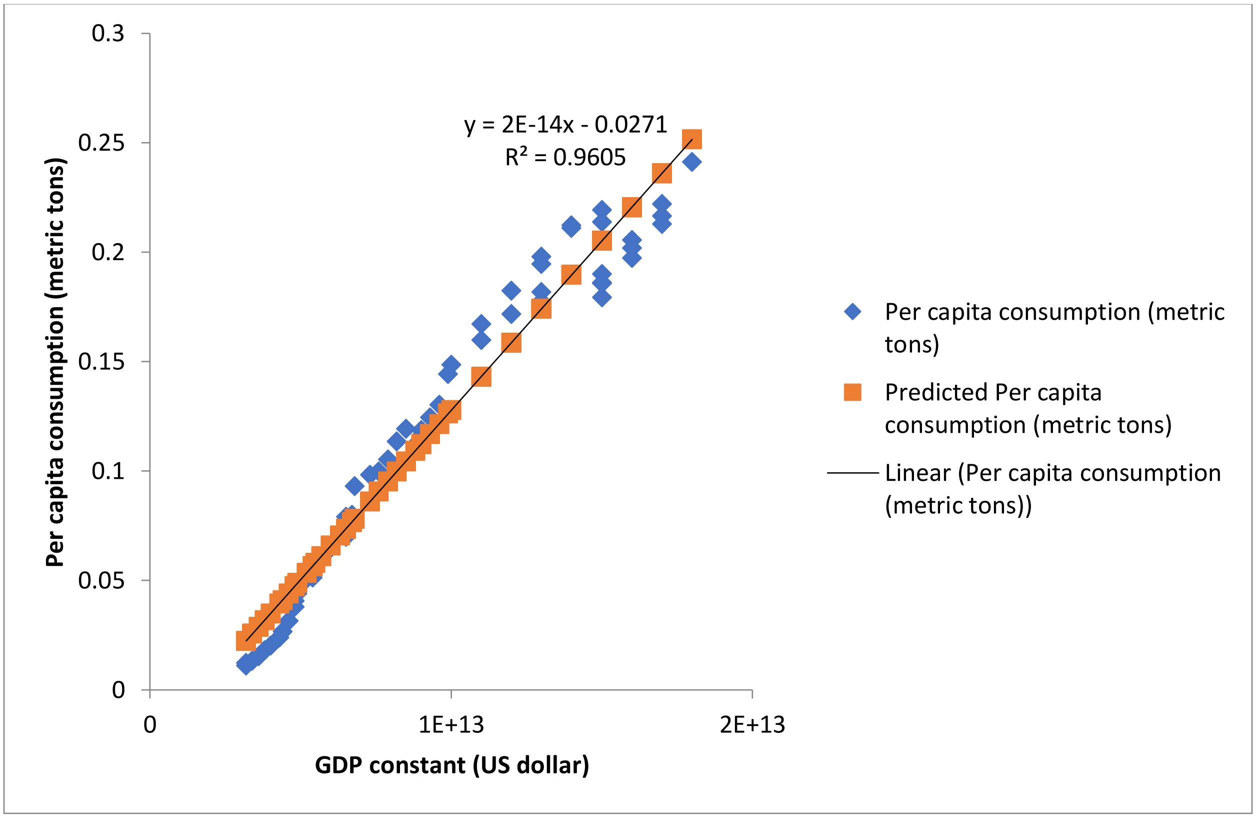

Table S3. Estimate the ratio of plastic shopping bag out of all packaging

Parameter	**Quantity**	**Reference**
Average plastic grocery bag consumption per household	1500 bags	(NRDC, 2008)
Number of households	116780000 household	(U.S. Census Bureau, 2020)
Average plastic grocery bag weight	5 grams	(Beachapedia, n.d.)
Total plastic bag consumption in 2008	8758.5 thousand metric ton	-
Total packaging consumption in 2008	18652.32 thousand metric ton	-

Ratio of plastic shopping bag out of all packaging	0.4702	-

Table S4. Summary of updated product lifetime (log-normal) distribution parameters in Scenario 4

Parameters	Lifetime (years)			ln(Mean/Sqrt(1+Var/SD^2))	Sqrt(ln((1+Var/Mean^2)
	Mean	Standard Deviation	Variance	μ	σ
Transport	20	7	49	2.937953103	0.3399
Packaging	1	0.1	0.01	-0.004975165	0.0998
Construction	50	15	225	3.868934157	0.2936
Electrical and Electronic Applications	10	4	16	2.22837509	0.3853
Household	10	2	4	2.282974736	0.198
Textile	10	2	4	2.282974736	0.198
Others	5[1]	1.5	2.25	1.566349064	0.2936

[1] Because the scope in "others" sector in different studies have variations, I did not change the parameters for this sector.

SEAS SCHOOL FOR ENVIRONMENT
AND SUSTAINABILITY
UNIVERSITY OF MICHIGAN

Deep Blue – Library License for Submitted Capstone

I hereby grant to the Regents of the University of Michigan the non-exclusive right to retain, reproduce and distribute the deposited work (the Work) in whole or in part, in and from its electronic format. This agreement does not represent a transfer of copyright to the University of Michigan.

The University of Michigan may make and keep more than one copy of the Work for purposes of security, backup, preservation and access, and may migrate the Work to any medium or format for the purpose of preservation and access in the future. The University of Michigan will not make any alteration, other than as allowed by this agreement, to the Work.

I represent and warrant to the University of Michigan that the Work is my original work. I also represent that the Work does not, to the best of my knowledge, infringe or violate any rights of others.

I further represent and warrant that I have obtained all necessary rights to permit the University of Michigan to reproduce and distribute the Work and that any third-party owned content is clearly identified and acknowledged within the Work.

By granting this license, I acknowledge that I have read and agreed to the terms of this agreement and all related University of Michigan and Deep Blue policies.

Author: Mengqing Kan Date April 22, 2
Author:____ Date__________
Author:____ Date__________
Author:____ Date__________
Author:____ Date__________
Author:____ Date__________

Capstone Type: Project ☐ Thesis ☑ Practicum ☐

Please submit this signed form along with your final capstone document and signed capstone verification form.

SEAS SCHOOL FOR ENVIRONMENT AND SUSTAINABILITY
UNIVERSITY OF MICHIGAN

Capstone Verification Form

Please upload this form along with the DeepBlue Licensing Agreement form to the Mbox folder or return completed form(s) to Jennifer Taylor, 1539 Dana, no later than 5PM on the **last day of scheduled classes** of the term in which the degree is expected

Title of Capstone Dynamic flows and stocks of plastics in the United States and pathways towards zero plastic pollution by 2050

Project No
(if applicable)

Capstone Type Project ☐ Thesis ☑ Practicum ☐ Integrative Seminar ☐

Key words/phrases Plastic pollution Dynamic material Scenario analysis Plastic waste

Client Name

Contact Name & Title Email

Student's Name	Specialization	UM ID	Email
Mengqing Kan	Environmental policy	75557565	akan@umich.edu

Advisor Signature(s) (print name and sign)

Ming Xu Digitally signed by Ming Xu
Date: 2021.04.23 09:32:34 +08'00' 4/23/2021

Name Date
Ming Xu

Chunyan Wang 数字签名者：Chunyan Wang
日期：2021.04.23 09:46:20 +08'00' 4/23/2021

Name Date

For office use only:

Date

Copy of the Capstone received
Presented Capstone
Form in student's file

SEAS SCHOOL FOR ENVIRONMENT AND SUSTAINABILITY
UNIVERSITY OF MICHIGAN

Capstone Verification Form

Please upload this form along with the DeepBlue Licensing Agreement form to the Mbox folder or return completed form(s) to Jennifer Taylor, 1539 Dana, no later than 5PM on the **last day of scheduled classes** of the term in which the degree is expected

Title of Capstone: Dynamic flows and stocks of plastics in the United States and pathways towards zero plastic pollution by 2050

Project No______________
(if applicable)

Capstone Type Project ☐ Thesis ☑ Practicum ☐ Integrative Seminar ☐

Key words/phrases: Plastic pollution; Dynamic material; Scenario analysis; Plastic waste

Client Name____

Contact Name & Title____Email__________________

Student's Name	Specialization	UM ID	Email
Mengqing Kan	Environmental policy	75557565	akan@umich.edu

Advisor Signature(s) (print name and sign)

____ 4/23/2021
Name Date
Ming Xu

____ 4/23/2021
Name Date

For office use only:

Date
___________ Copy of the Capstone received
___________ Presented Capstone
___________ Form in student's file

Last Revised 02/12/2020