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Article

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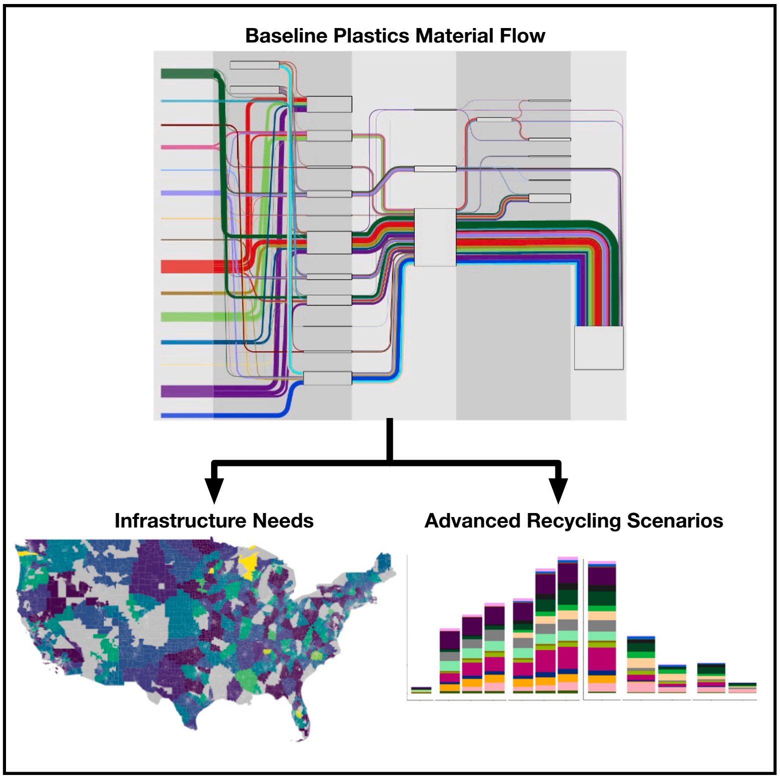
Graphical abstract



Highlights

- The United States consumed over 57 MMT of plastics but recycled less than 7% of this
- Commercial plastic recycling technologies can be scaled to reduce landfilling by 70%
- Sorting and recovery efficiency dictate the upper bound in recycling rates

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In brief

Our study establishes a material flow of US plastics from production to disposal, finding that less than 7% is recycled despite growing production and consumption. From this baseline, we develop a series of scenarios to increase plastic recycling using existing technologies, finding that almost 70% of waste could be diverted from landfills using commercially available technologies. We develop multiple scenarios for achieving near-zero waste in which waste flows to landfills are eliminated and recovered material increases by over a factor of 20.

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Paths to circularity for plastics in the United States

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SCIENCE FOR SOCIETY Global plastic waste generation will continue to grow rapidly. In the United States, the vast majority of plastic waste goes to landfills. Local governments, federal agencies, and private companies have set goals for increasing recycling and circularity, but require technical and implementation support to achieve waste reduction objectives. Policy makers, plastic producers, and the waste industry need clear information for existing waste flows, potential sorting and recovery technologies for scaling, and technological barriers for increasing recycling. In this study, we quantify flows of US plastics from production through disposal, finding that less than 7% of waste is recycled. From this baseline material flow, we develop scenarios for reducing waste flows to landfills, increasing recycling, and achieving greater plastics circularity.

SUMMARY

In 2019, the United States consumed over 57 million metric tons (MMT) of plastic with less than 7% recovered for reuse. This study provides an updated material flow analysis at national and regional scales for all durable and single-use plastics in the United States. From this material flow analysis, we develop a series of alternative future national plastic flow scenarios that envision a scale-up of recycling technologies, incorporating technical limitations and sorting infrastructure constraints. The results suggest that a maximum of 68% (24 MMT) of plastic waste could be diverted from landfills by scaling up existing commercial recycling technologies. Based on the current technological landscape, reaching near-zero waste is only possible if processes that are operating at pilot and laboratory scales can be effectively scaled and coupled with improved sorting infrastructure. Through these scenarios with increased recycling, the availability of postconsumer resin stocks could increase by 22–43 MMT.

INTRODUCTION

Global plastic waste generation has grown rapidly for several decades and will more than double by 2050, based on recent consumption growth rates.[1] In the United States, plastic waste disposal increased by almost 20% between 2010 and 2018, whereas the plastic recycling rate has declined in recent years and currently sits at less than 10% of total consumption.[2,3] The COVID-19 pandemic further accelerated this growth by necessitating greater consumption of single-use plastics for items such as disposable masks and gloves.[4] The cost and difficulty of producing high-quality recycled material from mixed municipal plastic waste streams, compounded by the low cost of virgin plastic resins, continues to hamper recycling efforts.[5] China's Operation National Sword policy initiative, which places restrictions on nonindustrial plastic waste imports, has further stressed US waste supply chains, forcing waste managers to seek alternative disposal pathways.[6,7] Municipalities, states, federal agencies, and corporations have set goals to reduce the landfilling of plastic waste,[8,9] yet our understanding of current plastics waste flows and which technologies are required to address them remains woefully incomplete.

A more granular understanding of how plastic makes its way from virgin resin to products and finally to wastes is crucial for achieving waste diversion goals. Several recent studies have attempted to quantify and describe plastic waste flows in the United States. Many previously published material flow analyses (MFAs) have focused on a single or select group of polymer or product types.[10–13] A handful of recent MFAs have addressed wider arrays of plastic waste, although they are hindered by data gaps, particularly on finished products.[3,5,14] The article by Di et al. considers most resin types but does not provide detailed information for less common plastics that do not have a dedicated plastic resin identification code (e.g., polyurethane [PUR], styrene butadiene rubber [SBR], acrylonitrile butadiene styrene [ABS]).[3] Milbrandt et al. focuses on landfilled plastic waste and does not address material-specific recycling pathways.[14] Of these recent MFAs, Heller et al. offers one of the most comprehensive analyses, considering a wide variety of polymer and application types.[5]

In this study, we quantify the potential for plastic waste recovery and recycling across the United States by tracking how individual polymer resins are incorporated into specific product types, matching product types with likely recovery rates based on current infrastructure and then identifying the range of conventional and advanced recycling processes capable of handling this range of materials. This study is the first to generate an economy-wide MFA accompanied by future scenario development and a geospatial infrastructure analysis. To develop the baseline MFA, our study expands upon the work of Heller et al. by updating data sources and further detailing the collection and sorting nodes in the reverse supply chain for products at their end of life (e.g., automotive waste). The future scenario results indicate that only approximately two-thirds of plastic waste could be diverted from landfills if all currently commercialized recycling technologies (e.g., mechanical recycling, glycolysis) were scaled up, assuming that waste flows to incineration are undesirable and either remain fixed or decrease. Furthermore, current sorting infrastructure, if not expanded, will require that more plastic waste be sent to higher-emitting pyrolysis processes that can accept mixed streams,[15] whereas investing in improved sorting can produce higher-quality plastic bales that are suitable for less carbon-intensive mechanical recycling processes.

Most important, we expanded our MFA to assess pathways to zero waste by developing scenarios for scaling up recovery technologies. We assessed US infrastructure needs by analyzing plastic waste availability and existing materials recovery facility (MRF) capacity at the census tract level, identifying where additional sorting infrastructure is needed to enable greater circularity. These results can inform both public and private investments needed to achieve waste diversion goals and increase the supply of post-consumer resin (PCR) across the United States.

RESULTS

National flows

Figure 1 shows the results of our baseline MFA. We estimate that over 57 million metric tons (MMT) of plastics were produced domestically, with 12 MMT being exported. Imports, both resin and finished products, accounted for 12 MMT of consumption. Polypropylene (PP) (8.6), high-density polyethylene (HDPE) (7.9 MMT), linear low-density polyethylene (LLDPE) (5.7 MMT), and polyvinyl chloride (PVC) (5.2 MMT) were the most commonly consumed plastics on a mass basis. Packaging was the top consumption category (17.2 MMT), followed by exports (12.1 MMT) and building/construction (8.3 MMT). We also found that a significant portion of plastics were consumed without a clear category of use (“other end-use markets,” 10.4 MMT). Of the plastics consumed in the United States, we found that 48 MMT were disposed of in 2019, resulting in an 8.8-MMT addition to the in-use plastic stocks. From the plastic waste disposed of, 77% goes to landfills, 13% is combusted with energy recovery, 6% goes to MRFs, 2% goes to electronic waste recycling, 1% goes to scrap film collection for film plastics, and 1% goes to “other beneficial reuse” (downcycled styrene butadiene rubber waste from tires). Only a little more than half (54%) of plastics sent to MRFs are actually recovered for domestic recycling. The rest is either exported as bales (29%) or landfilled (17%). Since the ban on exporting plastic waste to China, US bale exports go to Canada, Mexico, and Southeast Asia (Malaysia, Vietnam, Indonesia).[16] Full results for Figure 1 and the baseline MFA can be found in Tables S2–S5.

Waste reduction scenarios

Building on the MFA results, our waste reduction scenario results reflect the potential for diverting flows to landfills and increasing PCR stocks. In Figure 2, we show the flows to landfills across our modeled scenarios. Note that in Figure 2 the theoretical minimum scenario is not shown because this aggressive scenario would effectively stop all landfilling of plastic waste. Overall, flows to landfills within the United States are reduced from the current typical baseline by 56% (21 MMT, constrained sorting) and 77% (29 MMT, unconstrained) in the state-of-the-art scenario, and by 78% (29 MMT) and 92% (35 MMT) in the practical minimum scenario. Worth noting is the fact that bales of plastic waste exported internationally by MRFs are not included in these totals because there are no reliable data on how that waste is managed and what fraction is ultimately landfilled. The largest reductions are in HDPE and PP, with all HDPE being diverted (both state-of-the-art and practical minimum). This is because HDPE and PP are present in products whose physical characteristics (clear, three-dimensional) make recovery through conventional sorting technologies more feasible. It is also possible to pyrolyze mixed plastic waste containing large quantities HDPE and PP, whereas PVC cannot be processed through pyrolysis and any PVC contamination must be kept <2% due to corrosion and toxicity concerns.[17] Tables S6 and S7 show full scenario analysis results, and Figures S1 and S2 show Sankey diagram results for the theoretical maximum scenarios.

Figure 3 indicates the aggregate-level flows of plastic waste to each major recycling method. In all of the scenarios, mechanical recycling plays a crucial role in diverting waste from landfills. Increasing recovery rates of HDPE at MRFs will be essential to achieving this near-term increase in mechanical recycling. PP is also mechanically recycled in these scenarios, although due

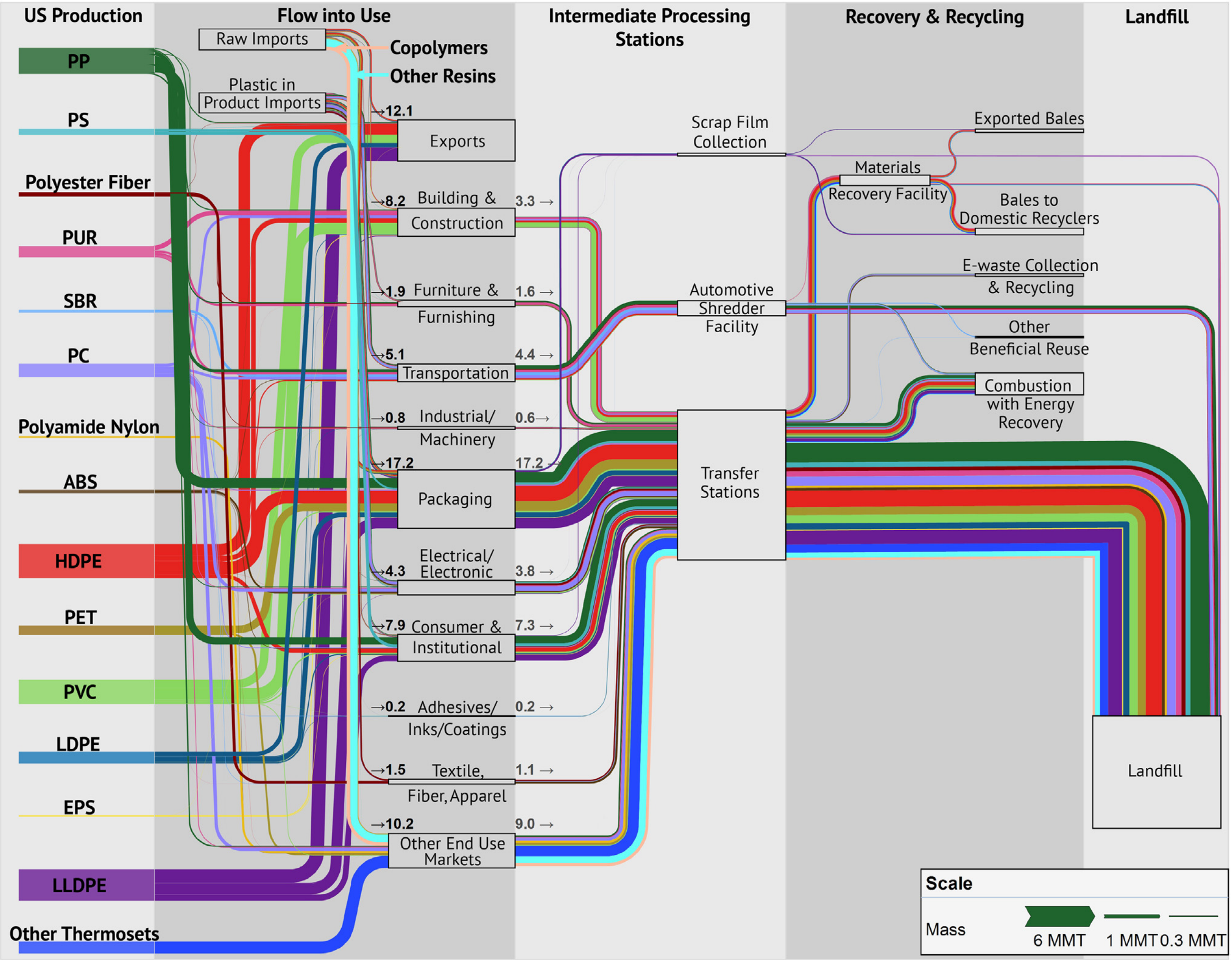

Figure 1. Baseline MFA results for US plastics flows in 2019

The values on the left and right of the consumption categories (see "flow into use" stage) reflect the tonnages (in MMT) into consumption and out to disposal (i.e., results from the in-use stock modeling). Note that recycled/reused materials will reenter consumption and disposal pathways. EPS, expanded polystyrene.

to its tendency to degrade in quality during mechanical recycling, we assume that a larger fraction must be routed to a more energy-intensive solvent-based process.[18,19]

Sorting plays a substantial role in sending waste to PCR recovery technologies in place of thermal conversion, particularly as emerging recovery technologies scale up in the practical and theoretical maximum scenarios. In our modeling, thermal conversion (pyrolysis, incineration) acts as a catch-all for difficult-to-sort plastics (e.g., films, electronics, furniture), but it does not contribute to PCR stocks and leads to additional environmental effects from processing and by-products. Because not all recyclable material is currently collected for recycling and recovered, more advanced sorting and processing technologies, such as hyperspectral imaging for separating low- and high-density polymers,[17] will enable more PCR generation through mechanical recycling. Sorting can also be coupled with solvent-assisted upgrading technologies, such as dissolution, to remove impurities (e.g., additives, dyes).[19] Pretreatment and prewash of plastic waste plays a crucial role in removing contaminants for recycling, and can be incorporated at the front end of an MRF or advanced recycling facility.[19] Although increasing the use of sorting equipment and adding lines in MRFs to separate additional resin types is not expected to have a dramatic impact on system-wide energy use, it will have a substantial impact on the capital and operating costs at these facilities.[18,19,20] Until markets for mechanically recycled material are saturated, improved sorting will continue to have circularity benefits and save energy.[19]

Figure 4 shows the increases in theoretical PCR stocks from our scenario analysis. Note that our Figure 4 results assume no losses (100% yield), and that incineration and pyrolysis have no PCR recovery. Each subsequent bandwidth scenario increases the PCR stocks as flows to recovery technologies increase. Even in the state-of-the-art scenario, PCR stocks increase by 21 MMT (constrained sorting) from the current typical baseline, with a maximum recovery of 46 MMT (unconstrained sorting) in the theoretical maximum, matching the total plastic waste generated in Figure 1.

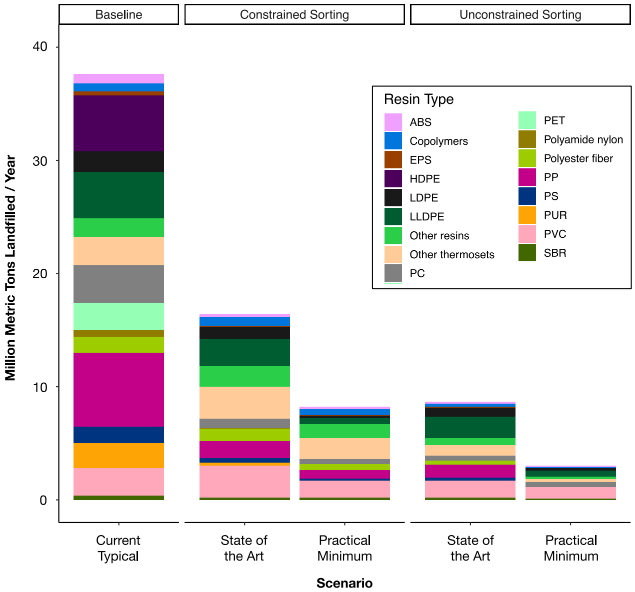

Figure 2. Plastic flows to landfills across each bandwidth scenario and sorting variation

Geospatial waste generation analysis

The national-level MFA provides a detailed summary of the greatest challenges in reducing plastic waste, but it does not capture regional variations and recovery/sorting constraints. Using analysis outputs from the BioSiting Webtool,[21] Figure 5 shows the results of our census-tract-level analysis for MRF plastic waste collection. In Figure 5A, we estimated plastic waste generation for each tract by taking the national average per capita plastic waste generation and applying each tract's population.[2] In Figure 5B, we used the results from Figure 5A and data from the nearest MRF to each census tract to estimate the share of total plastic waste that is currently collected at MRFs. In Figure 5B, we found that for MRFs that did report plastic waste data,[22] less than 10% of total plastic waste was collected by MRFs in most tracts, and as previously mentioned, only a portion of that collected waste will be recycled (i.e., "bales to domestic recyclers" in Figure 1). Together, the two figures show the potential for locating and scaling infrastructure to maximize landfill diversion and PCR production and the significant data gaps remaining in local waste generation, collection, and recovery. Comparatively high collection rates in the Northeast, Northwest, and Upper Midwest suggest that these are potentially promising locations to implement new advanced recycling technologies in the near term. The Southwest and the Central Valley of California appear to have relatively low collection rates and may benefit from additional collection infrastructure investment, although the data gaps in these regions are considerable.

Due to gaps in the available data, our geospatial analysis produced some outliers that must be interpreted with caution. In Figure 5B, the local variations are primarily driven by differences in population, and our analysis does not capture specific variations in per capita plastic waste generation rates due to a lack of available data. Plastic waste generation, for example, may be higher in more affluent areas where consumption of goods and services are higher. In addition, postindustrial waste is not differentiated here and this will not correlate with population; in fact, postindustrial waste may be some of the cleanest and most attractive waste to recycle.[23] The available data also do not clearly specify which areas are served by which MRF. To simplify the buffer analysis used in Figure 5B, we assumed that all of the tracts are served by at least one MRF, in the absence of data for which tracts were specifically served. This created unusually high recycling rates in a few low-population areas (e.g., southwest Washington, northeast Minnesota) where the nearest MRF was relatively larger than most and may serve tracts that are in fact closer to another, smaller MRF. These sources of uncertainty indicate that given the importance placed on diverting plastic waste by industry and federal agencies,[17,24] coordinated efforts to increase the overall collection and quality of data on the fate of plastic waste will be essential to measuring future progress and prioritizing investments.

DISCUSSION

In this study, we used MFA and scenario analysis to provide insights into potential pathways for increasing plastic waste recovery and diverting flows to landfills at a national level. The MFA reflects the relatively minimal amount of plastic waste being recovered, the scenario analysis reveals the significant potential for scaling up already commercially viable recovery technologies, and the geospatial analysis highlights the need for plastic waste recovery infrastructure across much of the country.

Costs, technology maturity, and product complexity are the primary barriers in achieving enhanced recovery. Recovery technologies are hampered by the cost of recycling, low value of PCR, and the low cost of virgin materials.[5] Many of the technologies in the practical and theoretical maximum scenarios are currently at pilot and lab scales, and without investment and success in scaling, will not become commercially viable. The diversity of polymers produced and consumed continues to increase without a focus on design for recovery. Recent legislation in California seeks to overcome recovery barriers by creating a required plastics extended producer responsibility (EPR) program, restrict consumption of polymer types based on recyclability, and increase plastic waste data reporting and collection at end-of-life facilities. Specific regulations, guidelines, and implementation plans are in development.[25,26] The European Union continues to be far ahead of the United States in its efforts to address plastic waste through bans on single-use products, over 2 decades of EPR requirements for producers, and mandatory minimums for recycled content in specific products.[27]

Scaling up sorting infrastructure and new recycling facilities (both mechanical and advanced) will not be simple; these facilities are likely to face permitting challenges and community opposition. Even current facilities can be forced to discontinue operations.[28] In the past, waste infrastructure has been placed in low-income and disadvantaged communities, concentrating local effects in burdened communities.[29,30] Avoiding these injustices of the past will require carefully considering where and how infrastructure is sited and how to minimize local community effects, such as traffic, noise, and air pollution.

Future research can refine the data and methods of this study while supporting implementation for plastic waste reduction and

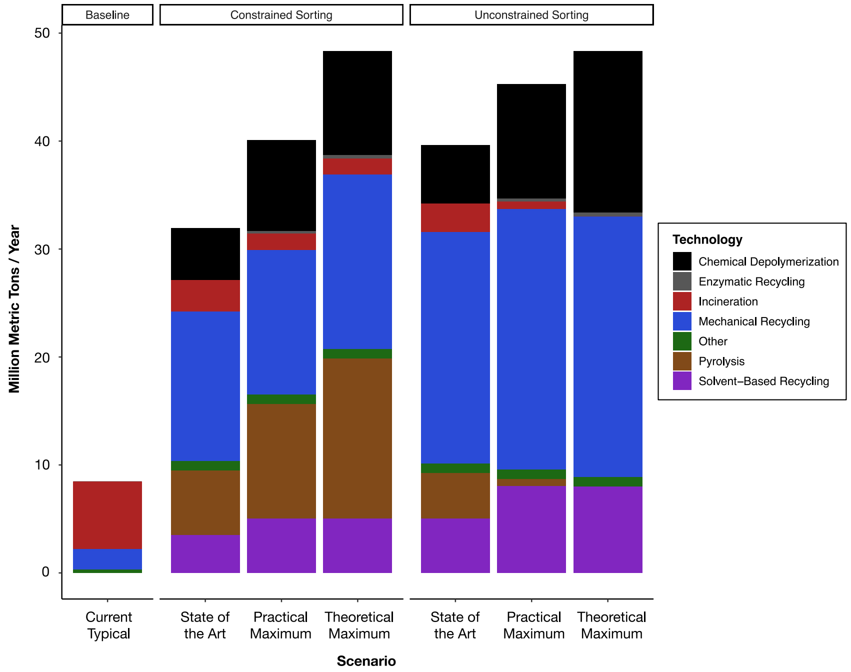

Figure 3. Plastic waste flows to recovery technology types across bandwidth scenarios

The technology type reflects each major recycling method to which the aggregate-level plastic waste flows.

recovery. Greater resolution in national and local flows for plastic waste, particularly in end of life, can overcome existing data gaps in annual consumption and disposal. This will provide greater insights into specific resin flows and enhanced geospatial detail in consumption, disposal, and recovery.

The results of this study are limited by the specificity and timeliness of available data. MRFs respond to market prices for bales of different waste types (both fiber and plastics), and these prices have been particularly volatile in the past few years. For example, US recycled plastics hit a record low price in October 2020, surged by almost 70% by August 2022, and then dropped by 20% before 2023.[31] Thus, US Environmental Protection Agency (EPA) data from 2018 may be limited in its representativeness of the current state of the recycling industry or what will occur in the future. In addition, this study does not consider material substitution, such as compostable plastics, which would not necessarily increase PCR stocks but could increase diversion from landfills. If and when waste diversion and recovery infrastructure scales up, the performance of recovery technologies, quality of outputs, and emerging markets for PCR will need to be monitored and analyzed for continued improvement. New waste recovery pathways will continue to emerge, such as recent advancements in polyethylene recovery.[32] Researchers and policy makers will need to clearly characterize and understand local effects from new infrastructure developments to minimize local effects. These ongoing efforts will help create a sustainable and successful shift in the production, consumption, and disposal of plastics.

EXPERIMENTAL PROCEDURES

Resource availability

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Materials availability

This study did not generate new unique materials.

Data and code availability

All original code and instructions have been deposited through GitHub at Zenodo at https://doi.org/10.5281/zenodo.10594857 and is publicly available as of the date of publication. We analyzed publicly available data, with the exception of two datasets: the American Chemistry Council Resin Review[33] and the Governmental Advisory Associates MRF Survey.[22]

National flows

To develop a baseline MFA of national plastic production, consumption, and disposal, we built upon the methods and data sources in recent studies,[3,5] with the goal of producing a more detailed and updated set of plastic flows through the US economy. In particular, our study provides new detail for product categories (“textile, fiber, apparel” in Figure 1) and for end-of-life supply chains and material flows through automotive waste, electronic waste (e-waste), and downcycling reuse (i.e., “other beneficial reuse” in Figure 1). Greater detail in waste product categories is essential to understanding how sorting constraints affect recyclability, given that form factor and the presence of multiple resins is important in determining whether items can be separated. By combining recent studies and industry reports, our research reconciled data gaps and generated a more thorough analysis by leveraging a wider array of data. Most important, our MFA provides a foundation for developing scenarios to model plastic waste reduction, generating a new application of MFA research in plastics.

For plastics production, we combined industry report data and the available literature to model the total production in 2019 for 15 different resins.[5,33] From this, we quantified flows from each resin into final products for 10 different categories (i.e., “flow into use” in Figure 1) by multiplying the relative share of flows into each category with the production tonnage to avoid discrepancies in production and consumption masses. We based product categories on those defined by the American Chemistry Council report.[33]

We used the methodology of Heller et al.[5] for modeling plastic imports (both raw and within products), using 2019 data from the US International Trade Commission (ITC).[34] For raw imports, we aggregated ITC import data using the ITC category descriptions and assumptions from Heller et al. We estimated total tonnage in raw imports by applying 2019 product values in US dollars (USD)/kg.[35] For plastics in imported products, we used methods from Heller et al. and updated data from the ITC. We pulled product import data for relevant commodities, and applied “plastic intensity” factors (in megatons of plastic per USD) from an industry report.[36] We then mapped these tonnages for each commodity to our consumption categories to estimate the specific resins imported in these commodities. The “copolymers” and “other resins” (see Figure 1) resin categories were unique to imports due to uncertainties in the ITC import categories. Table S1 provides further details on production and consumption data sources for each modeled resin.

A key challenge for annual snapshots of plastic flows through the economy is the short timescale; many plastics that were produced in 2019 were not disposed of in the same year, whereas plastics consumed in the past may be disposed of in 2019 depending on the polymer type and application. For example, plastics in packaging is very likely to be disposed of in the same year it is produced, but plastics in building materials may still be in use for decades before disposal. To capture this, we modeled “in-use stocks” using product lifetime distributions from Geyer et al.,[1] and applied those

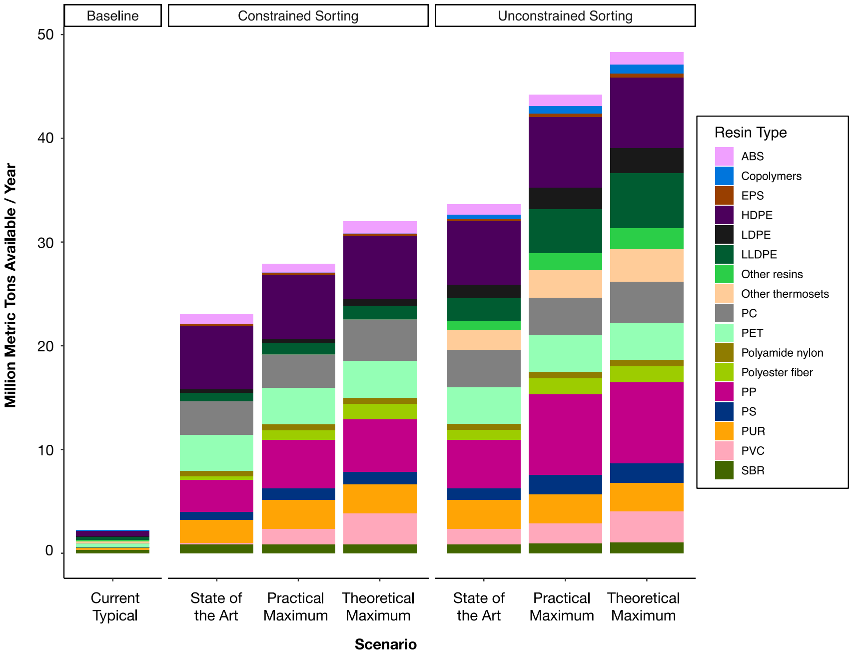

Figure 4. Theoretical PCR production with no losses across each bandwidth scenario and sorting variation

No PCRs are recovered in incineration or pyrolysis.

distributions to historical US plastics production data to estimate which plastics and how many were disposed of in 2019.[5]

After products are ready for disposal, they enter a waste management system that is highly variable depending on local waste collection practices and infrastructure. Some rural areas have no curbside collection service at all, whereas urban areas may offer separate curbside collection of recyclables, compost, and trash for landfill. For the purposes of the waste plastic flow analysis and future waste diversion potential, we modeled the system assuming all of the discarded plastics enter at least one initial intermediate collection facility (referred to here as a transfer station for most plastics, although actual terminology may vary) before further processing. Not all of the waste flows in our model move through a transfer station; based on discussions with industry experts and reports, plastic waste used in transportation is collected at an automotive shredder facility, and film plastics for recycling are collected at specialized scrap film facilities.[37] Automotive shredder facilities include end-of-life flows unique to SBR for transportation (i.e., tire waste), which is documented later in this section. A more detailed analysis of current sorting infrastructure limitations on a location-by-location basis is included in the subsequent section. Plastics used in transportation equipment (e.g., private vehicles, trains, buses), however, are modeled separately from other types of waste and handled in automotive waste facilities.

We then modeled plastic waste flows from collection facilities to final disposal. Of all of the recent literature, Di et al. provided the most detailed data for end-of-life waste flows to landfills, combustion, and recycling facilities (material recovery facilities, domestic recycled bales, and exported bales), but limited their scope to six resins (LDPE/LLDPE, HDPE, PP, polystyrene [PS], polyethylene terephthalate [PET], PVC) and an “other” category.[3] We used the flows from the “other” category combined with data and benchmarks from Heller et al.[5] and the EPA[2] to estimate the flows of PUR, polyester fiber, ABS, polyamide nylon, polycarbonate (PC), and SBR. We applied the EPA national average e-waste recycling rate[2] to all plastic waste generated from electronics consumption. For SBR used in transportation, we sourced data from the US Tire Manufacturer’s Association[38] to quantify flows to landfills, combustion (i.e., tire-derived fuel), and other beneficial reuse (e.g., tire waste for asphalt, aggregate, and ground rubber). We assumed any nontransportation SBR was landfilled. For remaining data gaps in flows from PUR, polyester fiber, ABS, polyamide nylon, and PC, we combined and compared data from the “other” category in Di et al.,[3] Heller et al.,[5] and the EPA,[2] and discussions with waste industry representatives to ensure that overall waste flows reflected results from recent analyses and flows at operating waste facilities. Full results for the baseline MFA can be found in Tables S2–S5.

Scenario development

Researchers and companies are developing and commercializing advanced recycling processes capable of producing higher-quality PCRs from mixed plastic waste.[32–39] In this research, we examine how conventional and novel recycling processes can be combined into a portfolio of solutions capable of addressing the complex range of single-use and durable plastic products used in the United States.

Starting with the baseline plastics MFA, it is possible to identify which product types are feasible to sort and how each type of material can be recycled. Using data on plastic waste generation and product types, we modeled scenarios for sorting and recovering that waste, finally matching recovered material with mature and emerging recycling technologies. Information on individual recycling technologies was sourced from national datasets, recent publications, coordination with industry experts, and industry reports. Table 1 shows a summary of the technologies used in the scenario analysis with the current scale and source.

It should be noted that the different end-of-life pathways in Table 1 can vary in their technological maturity depending on the resin to which they are applied. For example, mechanical recycling for PET and HDPE is common and commercialized, but mechanical recycling for PP is less common at commercial scale in the United States, in part, due to challenges in producing a high-quality PCR.[19] We took these specific resin differences into account in generating our scenarios, with full details on how each end-of-life pathway scaled for each resin in Tables S8–S13 and full results in Tables S6 and S7. For each end-of-life pathway, we assumed a maximum PCR yield efficiency with no losses (i.e., 100% yield efficiency). However, this can be thought of as a best-case scenario; in reality, there will be losses at each point in the reverse supply chain, in addition to the yield losses at recycling facilities themselves.

Although this study focuses on potential expansion of end-of-life technologies for plastic waste, sorting (typically done at MRFs) plays a critical role in the reverse supply chain and, in many cases, may be the bottleneck in boosting PCR production. Currently, US MRFs use manual, automated, or a combination of both approaches to sort plastic waste depending on the types of resins and total tonnage throughput being handled. Automated sorting is more advantageous at higher throughputs, creating substantial cost savings by sensing differences in the optical, chemical, and electrostatic properties of different waste plastics (e.g., optical and magnetic sorters). However, MRFs report tangling within the equipment (from films and fibers) and lower purity levels with automated sorting. Advanced automated sorting could overcome these challenges, including film plastic sorting, flake sorting to reduce contamination, and artificial intelligence-based sorting.[49]

We developed four separate plastic waste disposal scenarios (baseline, state of the art, practical maximum, and theoretical maximum) for estimating flows to landfills and PCR stocks. We based these scenarios on the methods used in US Department of Energy (DOE) bandwidth studies, typically used for estimating the potential of decarbonization technologies.[50] For the combination of each polymer and end-of-life pathway, we used the literature and industry reports cited in Table 1 to consider (1) the current and potential ease of sorting for each polymer with commercial and emerging sorting technologies; (2) the preprocessing and sorting requirements for each end-of-life pathway (i.e., accepting of multiple polymers or restricted to single

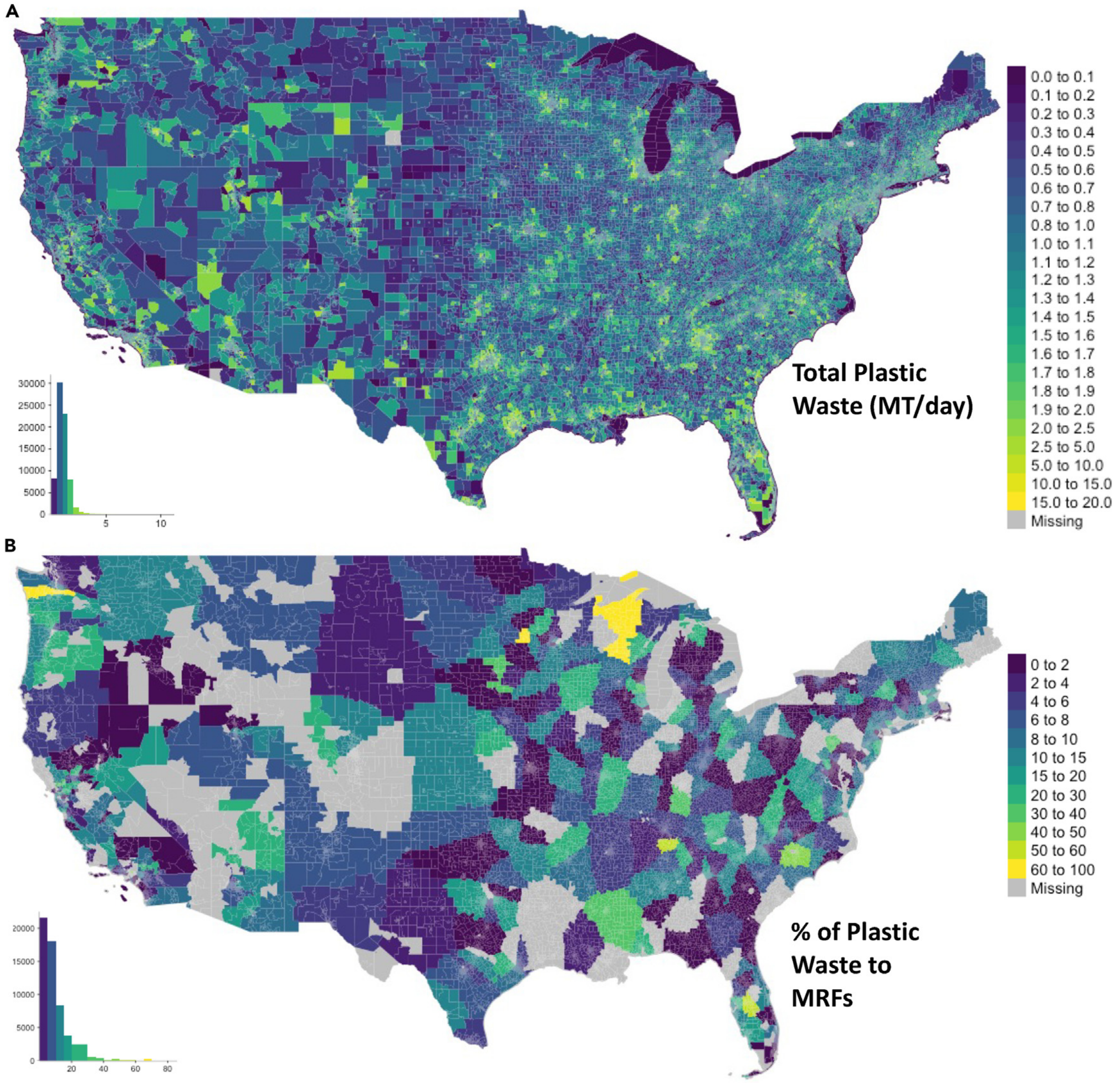

Figure 5. Geospatial infrastructure analysis results

(A) Plastic waste generation by tract based on population and national per capita plastic waste generation.

(B) The share of plastic waste collected at MRFs of total plastic waste generated, in which missing data reflected MRFs that did not provide data on plastic waste.

polymers); and (3) the current maturity for sorting, recovery, and other end-of-life technologies.

The DOE bandwidth study methodology provided qualitative guidance for scaling up technologies based on maturity level, which we applied across the four scenarios we developed in Table 2. Using the DOE framework, we gathered and synthesized the most relevant literature and reports shown in Table 1, along with industry expert feedback to characterize the current state of plastics recycling, and potential pathways for increasing plastic recovery and diversion from landfills. For most polymers, Table 2 shows the potential for sorting and recovery increases across scenarios as we assume, based on the DOE methodology, laboratory, demonstration, and commercial technologies scale up in subsequent scenarios.

In Table 2, the state-of-the-art scenario reflects the diverted flows to landfills and potential for PCR recovery by expanding the best-available technologies and practices available at commercial scale. This implies that technologies such as mechanical recycling and glycolysis (for certain polymers, such as PUR) will be further scaled up in this scenario and continue to expand in subsequent scenarios if other technologies are unavailable. In the practical maximum scenario, we begin to introduce and scale up technologies that are in the demonstration phase and further expanding commercially available technologies. In the theoretical maximum, or zero-waste scenarios (i.e., 100% landfill diversion), we introduce technologies that are operating only at laboratory scale and expand demonstration-scale and commercially available technologies if possible to reflect the theoretical potential if all technologies could be leveraged together successfully.[50] For all of the bandwidth scenarios, we have included the full details for how polymer waste flows were allocated across the end-of-life pathways modeled in Tables S8–S13.

For some polymers, we allocate high shares and sometimes the full waste flow to specific recovery technologies due to the unavailability of emerging recovery technologies through depolymerization or solvent-based technologies. An example is HDPE, which has one of the highest US recovery rates through mechanical recycling. Other polymers, such as PUR, have several depolymerization recovery technologies in development, each of which are scaled up in our scenarios, and as a result, the waste flow is more distributed than other polymers. It is possible that a subset of these options will prove more viable than the others, and future studies can be updated to reflect this evolution in the market.

Table 1. End-of-life pathways included in our analysis, with modeling details and sources

End-of-life pathway	Recycling type	Primary reagent (chemical recycling)	Accepted resins	Output products	Current scale	Operating entities	Source
Incineration	Combustion of plastic waste	N/A	All except PVC	Thermal energy	Commercial	Sites nationwide	US EPA, 2022[40]
Exported recyclables	Shipping plastic waste to international facilities for recycling	N/A	PUR, LDPE, LLDPE, HDPE, PP, PS, EPS, PVC, PET	N/A	Commercial	N/A	CalRecycle[41]
Mechanical recycling	Physical sorting, size reduction, and extrusion of single or mixed plastic waste streams	N/A	LDPE, HDPE, PP, PS, EPS, PVC, PET, PC	Clean, extruded resins suitable for virgin material replacement, downcycling, or further processing for reuse	Varies by resin	Sites nationwide	Li et al.,[17] Nordahl et al.,'[19] NexantECA,[39] Damayanti et al.[42]
Ammonolysis	Chemical depolymerization	Ammonia (PET) or 4-dimethylaminopyridine (polyamide)	PET, polyamide nylon	PCR monomers	Lab		NexantECA[39]
Glycolysis	Chemical depolymerization	Monoethylene glycol	PUR, PET, polyamide nylon, PC	PCR monomers	Varies by resin	Aquafil, Axens, Eastman, Garbo, Ioniqa, perPETual Global Techs, Petrobras, Poseidon Plastics, Starkweather Labs, Teijin Chemicals, JEPLAN, IBM	Li et al.,[17] NexantECA,[39] Damayanti et al.,[42] Chen et al.[43]
Hydrogenation	Chemical depolymerization	Hydrogen	PUR, polyamide nylon, PET	PCR monomers	Lab		Li et al.,[17] NexantECA[39]
Hydrolysis	Chemical depolymerization	Water	PUR, PET, polyamide nylon, PC	PCR monomers	Varies by resin	Circ, Gr3n, Loop Industries, RESYNTEX, DePoly	Li et al.,[17] NexantECA,[39] Damayanti et al.[42]
Enzymatic recycling	Enzyme-based recovery	N/A	PET	PCR monomers	Pilot	Carbios	Li et al.,[17] Tournier et al.,[44] Knott et al. 2020[45]

(*Continued on next page*)

Table 1. *Continued*

End-of-life pathway	Recycling type	Primary reagent (chemical recycling)	Accepted resins	Output products	Current scale	Operating entities	Source
Aminolysis	Chemical depolymerization	Dibutylamine, ethanolamine, lactam, alkanolamine, methylamine, ethylamine	PUR, PET, PC	PCR monomers	Varies by resin	Dow Chemical	Li et al.,[17] NexantECA,[39] Damayanti et al.[42]
Methanolysis	Chemical depolymerization	Methanol	PET, PC	PCR monomers	Varies by resin	Eastman, Loop Industries	Li et al.,[17] NexantECA,[39] Damayanti et al.[42]
Pyrolysis	Thermal conversion	N/A	All except PVC	Plastic pyrolysis oil	Commercial	Agilyx, Pyrowave	NexantECA,[39] Damayanti et al.,[42] Jeswani et al.[46]
Acidolysis	Chemical depolymerization	Hydrochloric acid, succinic acid	PUR	PCR monomers	Pilot	RAMPF Eco Solutions, H&S Anglagentechnik	NexantECA,[39] Luo et al.[47]
Phosphorolysis	Chemical depolymerization	Phosphonic acid, phosphoric acid	PUR	PCR monomers	Lab		NexantECA[39]
Supercritical butane solvent process	Chemical solvent-based	Supercritical butane	PP	PCR polymers	Commercial	PureCycle	Li et al.,[17] Vollmer et al.[21]
Cymene solvent process	Chemical solvent-based	Cymene	PS	PCR polymers	Commercial	Polystyvert	Li et al.,[17] Vollmer et al.[21]
Tire product recovery	Physical downcycling of SBR into tire-derived products	N/A	SBR	Downcycled products	Commercial	Sites nationwide	CalRecycle[48]

N/A, not applicable.

Table 2. Recovery and sorting technology scale up for each polymer across the 4 "constrained sorting" scenarios modeled

	Sortability				Recoverability			
Polymer	Baseline	State of the art	Practical maximum	Theoretical maximum	Baseline	State of the art	Practical maximum	Theoretical maximum
ABS	+	++	+++	+++	+	++	++	+++
Copolymers	O	O	O	O	O	O	O	O
EPS	O	+	+	+	O	O	++	+++
HDPE	++	+++	+++	+++	++	+++	+++	+++
LDPE	O	+	+	+	O	+	++	+++
LLDPE	O	+	+	+	O	+	++	+++
Other resins	O	O	O	O	O	O	O	O
Other thermosets	O	O	O	O	O	O	O	O
PET	++	+++	+++	+++	++	+++	+++	+++
Polyamide nylon	+	++	+++	+++	+	++	+++	+++
Polycarbonate	+	++	+++	+++	+	++	+++	+++
Polyester fiber	O	O	O	O	O	O	O	O
Polyurethane	+	++	+++	+++	+	++	+++	+++
PP	O	+	++	++	O	+	+++	+++
PS	O	+	++	++	O	+	+++	+++
PVC	+	++	+++	+++	+	++	++	++
SBR	+	++	+++	+++	+	+++	+++	+++

"Sortability" reflects the ease of sorting, whereas "recoverability" is the potential for generating PCRs based on the technologies studied. The number of plus signs in each cell indicates the general level of how much can be sorted and recovered for each polymer. Cells with "O" reflect a polymer that cannot be sorted or recovered. To view complete allocation details for each polymer and end-of-life pathway, see Tables S8–S13.

Some polymers have specific restrictions or uncertainty in the data. In Table 2, polyester fiber is considered difficult to recover due to the challenges associated with textile contamination (e.g., broken glass, moisture) in municipal waste sorting facilities. However, textile take-back programs and separate handling facilities, which are not modeled here, may be capable of overcoming these challenges.[51]

For each of the four scenarios, we modeled "constrained" and "unconstrained" variations for sorting at collection facilities. The constrained variation reflects currently available technologies, whereas unconstrained variation shows a theoretical potential of recovery in which limits on sorting are removed and waste flows to recovery pathways are not impeded by losses in sorting.

For each scenario in Table 2, we identified the fraction of each plastic type that would be present in separated single-resin streams and fractions that would be present in mixed waste bales. Using that information, waste streams were routed to technologies that would produce virgin or downcycled PCRs whenever possible. Beyond the recovery pathways, we then allocated flows to pyrolysis, incineration, and landfills, in that order of priority. In all of the scenarios, we set a maximum limit of 10% for the waste flow of each polymer that could go to incineration. For pyrolysis, we set a maximum of 30% and 60% of each flow that could go to pyrolysis for the state-of-the-art and practical maximum scenarios, respectively, and assumed that there would be no limit on pyrolysis capacity in the theoretical maximum scenario. Note that PVC in our modeling is not eligible for incineration or pyrolysis due to toxic releases and metal corrosion.[42,52] Not included in our study, gasification with syngas generation is an alternative to incineration and pyrolysis for landfill diversion without PCR recovery.[53]

Tables S8–S13 show a summary of the allocations for the waste flow of each polymer to each disposal pathway. We reviewed these allocation assumptions with technical and industry experts and designed the model for flexibility to generate additional and future scenarios. Tables S6 and S7 show the full results for the scenario analyses for annual flows to landfills and PCR generation.

Geospatial waste generation analysis

As noted in the previous section, existing sorting infrastructure is a key bottleneck in the system. Most MRFs only separate PET and HDPE, and based on the types of physical and optical sorting processes in use today, clear, three-dimensional items are most likely to be recovered successfully. To gain a perspective on regional variations in plastic waste generation, our team developed a database of census-tract MRF plastic waste collection. The Joint BioEnergy Institute and the Lawrence Berkeley National Laboratory developed the public BioSiting Webtool, available at lead.jbei.org, as part of the BioC2G modeling package, to allow users to explore the available bioenergy resources within a given area.[21] As part of this research, our team incorporated the MFA data sources into the BioSiting tool with the goal of modeling the availability of postconsumer materials from local MRFs.

We developed a national inventory of MRF locations and plastic waste collected using national survey data for MRFs.[22] These survey data provide collection tonnage and waste stream composition data for MRFs throughout the country. To overcome gaps in the available MRF waste flow data, we assumed that sorting and recovery technologies were consistent across MRFs, creating potentially higher material availability estimates than actual MRF operations. Some MRFs reported no plastic waste collection in their survey responses.

We combined this MRF inventory with the most recent US Census tract-level data in a buffer analysis to determine the closest MRF to each Census tract. We generated an estimate of plastic waste collected daily in each Census tract by allocating the collected waste of each MRF to the serviced tracts based on tract population relative to the total MRF service population. To understand what share of plastic waste is being collected by MRFs, we estimated the total plastic waste generated by each tract by applying the national daily per capita plastic waste generation rate to the population of each tract using 2019 data.[2] Using a national average limits our ability to capture regional granularity, but one recent study found population density to be the best parameter for estimating plastic waste generation in lieu of local data.[14] From the tract-level estimates for plastic waste generated and collected, we plotted both the total generation in each tract and the share of that waste collected at an MRF.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.02.005.

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AUTHOR CONTRIBUTIONS

Conceptualization, T.P.H., N.V., B.A.H., and C.D.S.; methodology, T.P.H., B.B., N.V., T.H., S.N., B.A.H., and C.D.S.; software, T.P.H., B.B., N.V., T.H.; investigation, T.P.H., N.V., S.N., B.A.H., and C.D.S.; data curation, T.P.H., B.B., N.V., T.H., and C.D.S.; writing – original draft, T.P.H. and C.D.S.; writing – review & editing, T.P.H., B.B., N.V., T.H., S.N., B.A.H., and C.D.S.; visualization, T.P.H., B.B., T.H., B.A.H., and C.D.S.; supervision, T.P.H., B.A.H., and C.D.S.; project administration, T.P.H. and C.D.S.; funding acquisition, B.A.H. and C.D.S.

DECLARATION OF INTERESTS

B.A.H. and C.D.S. have a financial interest in Cyklos Materials.

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