DIFFERENT STROKES FOR DIFFERENT FOLKS: A SPATIAL ANALYSIS OF INVESTMENTS NEEDED TO INCREASE THE UNITED STATES POST-CONSUMER PLASTIC COLLECTION RATE

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Abstract. The United States generates 42 Mt of plastic waste significantly contributing to ocean plastic waste. Plastic has become synonymous with the linear economy, and many stakeholders are studying and proposing resource efficient solutions to mitigate plastic pollution. Recycling has received much attention from both social sciences and engineering, but a limited number of studies have quantified how behavioral interventions could asymmetrically affect different populations. This study further develops the plastic parallel pathway platform (4P) – a plastic recycling agent-based model combined with dynamic material flow analysis, and life cycle assessment that can analyze the effect of behavioral interventions on the collection rates of different waste streams. Results for polyethylene terephthalate (PET) and high-density polyethylene (HDPE) show that an intervention increasing access to recycling programs could improve collection rates by about 20 percentage points (pp) and that the efficacy of the intervention highly depends on the social context. For instance, in South Dakota, a 31 pp gain is achieved for approximately $300 million investment. In contrast, Louisiana sees the largest absolute gain in PET collection (36 pp) but at a higher cost ($2 billion). Increasing access to recycling programs could save about 0.2 million metric tonnes of carbon dioxide (CO2) equivalent per year if the plastic waste is mechanically recycled.

Keywords: Resource efficiency, plastic recycling, agent-based modeling, recycling behavior.

1 Introduction and Motivation

About 400 million metric tons (Mt) of plastics are consumed every year and 9 to 14 Mt of them end up in aquatic ecosystems [1, 2]. Such aquatic pollution may cause physical and chemical harm to marine species such as turtles, fish, and birds through entanglement, starvation, and perforation [3] and also possibly to human life [4, 5].

The United States (US) generates 42 Mt of plastic waste each year and is one of the biggest contributors of ocean plastic waste (around 1 Mt), mostly due to littering and illegal dumping [6, 7]. Less than 9% of all US plastic wastes are recycled, which translates into an estimated annual energy and value loss of 3.4 EJ and $7.2 billion, respectively [8].

Nowadays, plastics are synonymous with the linear or “take-make-waste” economy [9]. In contrast, resource efficiency (RE) strives to keep materials and products at their highest value – reducing waste and environmental impacts. RE strategies such as reducing, reusing, and recycling plastic waste could mitigate plastic pollution [10] and contribute to reaching net-zero emission plastics [11]. Indeed, Meys, Kätelhön [11] demonstrate that reaching fully net-zero emission plastics using only carbon capture and utilization (CCU) and biomass substitutes is not possible – even when lower-emitting energy is used. Conversely, adding circular carbon pathways to the plastic system (on top of CCU, biomass, and RE) leads to slightly net-negative plastics [11].

At 32% inclusive of all materials, the US recycling rate is lagging behind other developed countries [12, 13]. Indeed, significant challenges still hinder plastic recycling [13, 14]. First, the quality of the recycled resin is difficult to maintain with current mechanical recycling technologies [9]. Second, both the quality and quantity of collected plastic waste need to be improved [13, 14]. Besides new infrastructure investments, targeting consumer behaviors is key to enhancing the collection rate of plastic waste. Making it easier for consumers to recycle through better access to recycling programs along with education campaigns could boost the volume of collected recyclables and reduce contaminations [15].

2 Review of Related Work

Part of the waste generation problem is under the control of individuals – along with companies’ choices, such as what packaging materials they use. Indeed, people make conscious decisions regarding waste reduction and production [16]. They decide what to do with their waste; for instance, whether a particular piece of waste should end up in the trash or the recycling bin. To help understand what motivates people to recycle and design effective interventions researchers may turn to the field of environmental psychology, which has a long tradition of finding the root cause of pro-environmental behaviors [16].

Overall, recycling behaviors are highly contextual as they depend on many factors [16]. Adapting to social contexts may be key to efficiently improving the quantity and quality of collected plastic waste in the US. Thus, a spatial, behavioral analysis may enhance our understanding of the problem [17, 18].

Many studies have been published on the US plastic recycling system. Some characterize national [8, 13, 14, 19, 20] or subnational [21] material flows; others explore technological solutions [9, 14, 19, 22] or assess the environmental impacts and economics of recycling [23, 24]. Some studies also focus on consumer behaviors [25-27]. However, few studies have yet investigated the divergent effect of behavioral interventions on diverse populations.

To fill this gap, this research further extends a previous agent-based modeling (ABM) study [28], increasing its geographical resolution, material scope, and actionable insights. The aim of the study is to understand how increased access to recycling programs and consumer education could improve plastic collection rates and what investments could be needed to do so. The following sections will present the model and discuss results obtained in baseline and intervention scenarios.

3 Technology Approach

To model household recycling behaviors and the effects of access-based and education interventions, we use an ABM developed in Walzberg, Sethuraman [28] and Ghosh, Uekert [29] and part of a larger dynamic material flow analysis and life cycle assessment framework, the plastic parallel pathway platform (4P). The ABM simulates three plastic waste disposal decisions for household agents: recycling, wish-cycling (placing non-recyclables in recycling bins), and disposal into the trash bin. The ABM is well-suited for modeling the plastic waste system because it preserves heterogeneity in agent behavior and their social context. This allows exploring both individual- and system-level interventions – such as infrastructure expansion and education campaigns – while maintaining a high geographic resolution.

The model incorporates psychological determinants (e.g., cognitive and financial effort, attitude towards recycling, and social norms) and structural factors (e.g., access to subscription and curbside recycling programs). The data used to measure and weight the effects of those factors on the agents' decisions are grounded in empirical social-psychology literature and validated with national and regional data on recycling behavior [28, 30]. Moreover, habits were also included in the model. Indeed, for behaviors such as waste disposal, individuals often act out of habits (independently of the factors mentioned above) [16]. The model from Taghikhah, Voinov [31] was adapted to represent this habitual component of agents' behavior. The equation below summarizes the probability P_{ij}^{t} that agent i enacts the specific behavior j at time t [28].

$$P_{ij}^{t} = \begin{cases} 1 \; for \; past \; behavior \; j \; if \; habits \; conditions \; are \; met \\ BI_{ij}^{t} \end{cases}$$

With BI_{ij}^{t} a probability defined according to the psychological determinants and structural factors described above. When agents act out of habit, they simply choose the same behavior they have been choosing in the past. According Lally, van Jaarsveld [32], 70 repetitions of the same behavior are necessary to form habits, which is the value we chose in our model.

The model was parametrized using data from The Recycling Partnership [33], socio-economic indicators from U.S. Census Bureau [34], and other sources (see Walzberg, Sethuraman [28] for the full list). For instance, a dataset on the distribution of households with access to curbside recycling or on-property multifamily recycling across the United States was used to define one of the structural factor affecting agents behavior [28, 33] and the level of education across different U.S. counties was used to account for the level of knowledge regarding recycling [34].

We used the ABM to model three scenarios:

- A baseline in which behavioral determinants and access rates are held constant throughout the simulation.
- An improved access scenario in which access to curbside and subscription recycling programs expands linearly, eventually reaching all U.S. counties.
- An increased education scenario in which agents' knowledge about recycling expands linearly, eventually reaching a 100% knowledgeable population.

For this study, 4P was enhanced to provide estimations at the county level (instead of state level) using higher resolution datasets from the U.S. Census Bureau [34] and The Recycling Partnership [33] and was extended to include another plastic than polyethylene terephthalate (PET): high density polyethylene (HDPE) (using the same data sources). The ABM was validated using EPA-reported PET and HDPE collection rate data from 2021. Estimated county-level collection rates showed a mean absolute error of 5% for PET and 4% for HDPE.

4 Discussion

In the improved access scenario, the average national collection rate for PET and HDPE increases from about 22% (in the baseline) to approximately 42%. Figure 1-a illustrates the existing landscape of curbside and subscription access across US counties, showing that over 35% of households currently lack access. In Figure 1-a, access levels vary widely between and within states. Figure 1-b displays the projected improvements in county-level PET collection rate in the improved access scenario. The most significant gains are observed in counties with low baseline access, particularly in southern and mid-Atlantic states. In contrast, states with bottle bill programs but limited curbside access (e.g., Maine) see relatively smaller improvements, reflecting high baseline collection rate achieved through deposit return systems (DRS)[1].

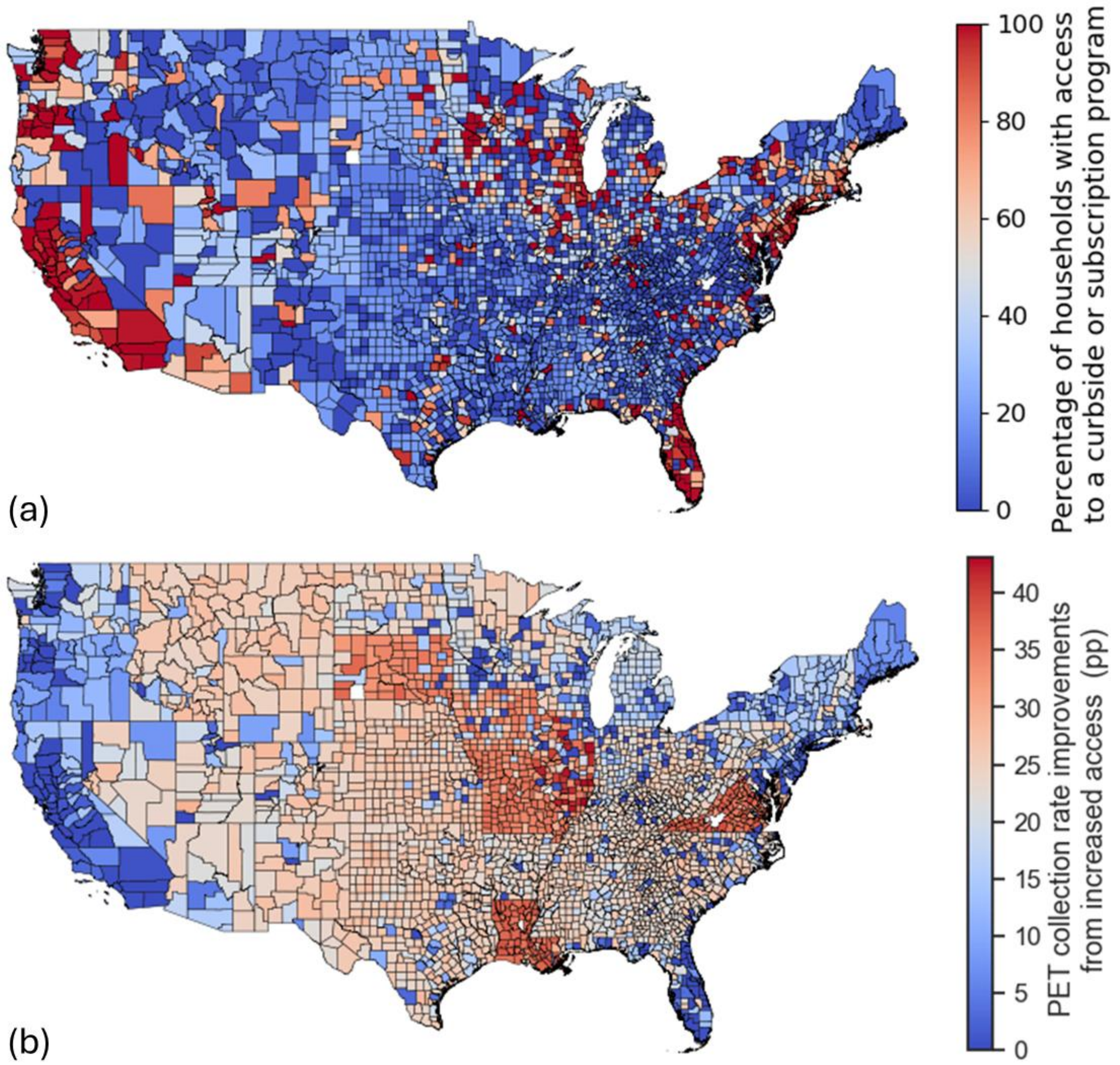

Fig. 1. *Impact of interventions on the US PET collection rate (a) current household access to curbside and subscription recycling programs by county. (b) Percentage point increase in PET collection rate (improved access collection rate – baseline collection rate) under the improved access scenario (2020–2050).*

[1] In the US, DRS and bottle bills are essentially synonymous, although technically the former are recycling mechanisms, which are independent from any specific policy, while the latter are state programs that rely on DRS.

Results for HDPE exhibit similar patterns, though some differences emerge: the West Coast and parts of the Northeast (e.g., New York and New England) show greater increases in HDPE collection compared to PET. This can be explained by the lower prevalence of HDPE in bottle bill redemption systems relative to PET.

According to Figure 2, South Dakota counties would be – on average – the most cost-effective for an improved access intervention. A 31 pp gain could be achieved with an approximate investment of $300 million. Louisiana would see the largest absolute gain in PET collection rate (36 pp) from the intervention, but at a higher cost ($2 billion). Once again, results for HDPE reflect similar regional efficiency patterns.

Figure 3 presents the difference in projected improvements in county-level PET collection rate in the improved access and increased education scenarios. Similar to the improved access scenario, states with DRS already have high collection rates explaining that increased consumer education has a low effect on the agents' behaviors. However, recycling knowledge differences across counties in the baseline are less pronounced than differences in recycling program access, causing the effects of the increased education scenario to be more equally distributed than the effects of the improved access scenario. This notable result could be relevant to policymaking, for instance, to determine which intervention would be better suited to achieve specific goals (e.g., reducing inequalities in recycling rates or improving overall material collection).

Using the MFA and LCA capabilities of 4P [29], we find that the improved access and increased education interventions could each avoid about 0.2 million metric tonnes of CO_2 equivalent per year and increase the plastic system RE by 3% (as calculated by the material circularity indicator (MCI) [35]) if all the collected plastic is mechanically recycled. Chemical recycling could enhance those indicators even further. If all the collected plastic is recycled through glycolysis, the improved access and increased education interventions would each avoid about 0.3 million metric tonnes of CO_2 equivalent per year and increase the plastic system RE by 7% (as calculated by the MCI).

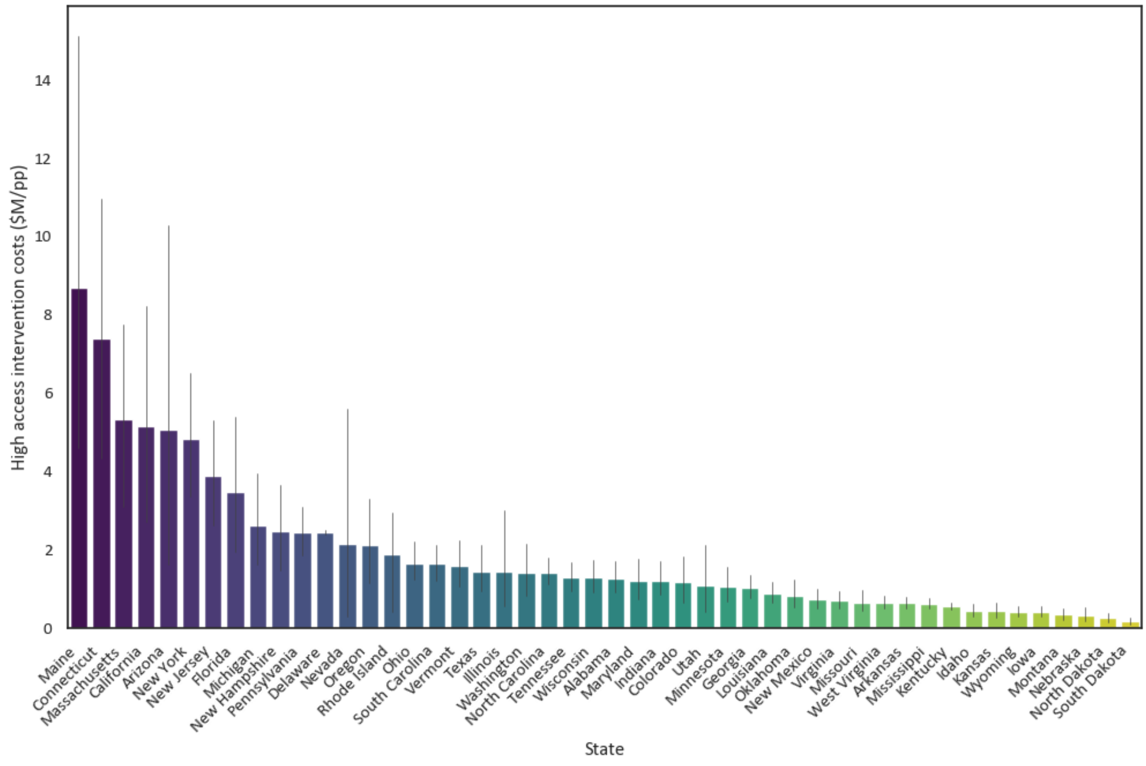

Fig. 2. *Intervention cost-effectiveness for PET recycling under the improved access scenario. The figure shows total cost (2020–2050, in million dollars) per percentage point increase in collection rate. Only counties with changes greater than 0.5 pp are included in the figure and error bars indicate the 95% confidence interval.*

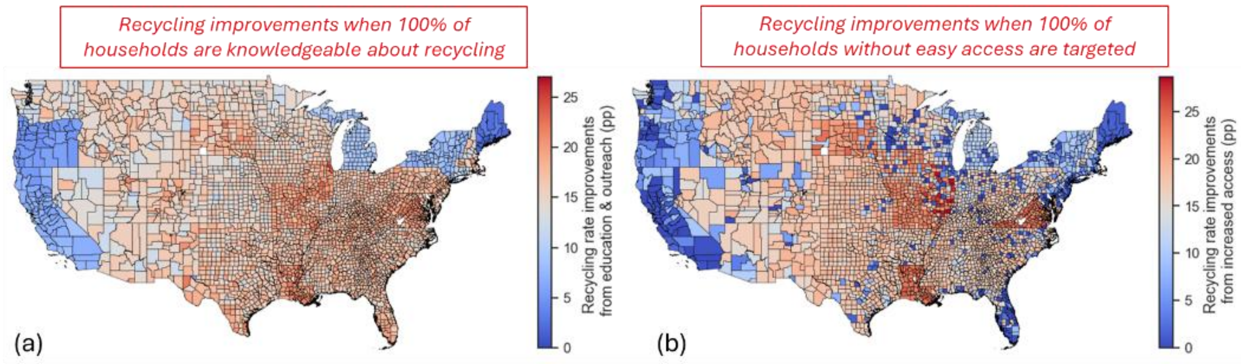

Fig. 3. *Impact of interventions on the US PET collection rate (a) Percentage point increase in PET collection rate (improved access collection rate – baseline collection rate) under the increased education scenario (2020–2050). (b) Percentage point increase in PET collection rate under the improved access scenario (same plot as figure 1-b, shown for comparison).*

The higher improvement in RE (MCI) when compared to emission reductions between mechanical recycling and glycolysis is due to glycolysis being a closed-loop recycling process – where PET bottles can be recycled into new PET bottles – and mechanical recycling provides feedstock mostly to downcycling applications (such as for the textile industry). This explains why the glycolysis MCI is more than double that of mechanical recycling. This result is in line with prior literature which demonstrated the differences between PET bottles closed-loop recycling and downcycling applications [24]. The recycling processes do not differ as much in terms of energy use and emissions, causing a smaller discrepancy (67% more avoided emissions for glycolysis).

Disposing something into the trash or recycling bins is often considered uninteresting routine behavior. To change such habitual behaviors for the better (i.e., getting more individuals to correctly recycle different waste packaging and materials), structural and educational investments are needed. This study demonstrates that the developed ABM – by capturing habits and external factors affecting disposal behaviors – can provide insights into what level of investments into the U.S. recycling system are needed and where they should be prioritized (Figure 2). Combining the ABM with the MFA and LCA capabilities of 4P also shows that environmental and waste diversion benefits of recycling can be estimated, providing additional arguments for prioritizing one type of investment over another. Since recycling processes mostly use electricity as their energy input, this conclusion is even more relevant when regional evolutions of the grid are considered with a model such as the NLR's Regional Energy Deployment System model [36].

5 Conclusions & Recommendations

These findings emphasize the importance of geographically targeted interventions – something that ABM can capture well, allowing for deep spatial analysis. Counties and states with limited access to recycling programs represent the greatest opportunity for scalable and cost-effective improvements in PET and HDPE waste collection. While increasing access to recycling programs is necessary, the results highlight that it is not sufficient alone. Indeed, Figure 1 shows that when all agents have access to such programs, the collection rate certainly improves significantly but caps at 42%. Other factors – including social norms, knowledge about recycling, and infrastructure capacity – also need to be addressed to increase the collection rate further, as exemplified in Figure 3. Interestingly, acting on factors such as the level of knowledge about recycling has a more distributed effect than acting on structural factors such as the access to recycling programs. Future work will study the effect of combined interventions (e.g., increased education *and* improved access) and expand the model to include more materials (e.g., aluminum cans or organic waste). For instance, because other types of plastics have different usages (e.g., other than packaging), collection rates, and recycling technologies, the developed ABM could yield complementary insights, improving the overall comprehension of the plastic recycling system.

Acknowledgments

This work was authored by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Critical Minerals and Energy Innovation Advanced Materials and Manufacturing Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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