An Agent-Based Modeling Approach for Informing the U.S. Plastic Waste Management Process

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***Abstract*— Recycling is one of the most significant issues in the waste management system. As the use and demand for plastics increase every year, finding efficient and environment-friendly solutions to handle the plastics in the plastic waste management system gets more challenging. There are economic, environmental, and educational factors affecting plastic waste management. This paper investigates the effects of educational campaigns and system-wide improvement. For this, we used an Agent-Based Modeling and Simulation approach in the NetLogo environment. We provided various scenarios in the current plastics waste life cycle using a real dataset to validate our model, which was from the American Chemistry Council and the National Association for PET Container Resources from 2018. We found that education, technology, and infrastructure changes should be considered holistically to overcome this problem at a system level.**

Keywords-Agent-Based Modeling; NetLogo; Recycling; Plastic Waste Management

I. INTRODUCTION

The demand for plastics increases every year, and over 300 million tons of plastics were produced in 2018. All of these plastics meet one of three fates within the plastic waste system: (1) recycling and reproduction, (2) thermal destruction (combustion with energy recovery), and (3) landfill deposition. Recent estimates of the fates of all plastics ever made indicate that only 9% was recycled, 12% was incinerated, and 79% was deposited in landfills or discarded in natural environments, such as the oceans [1][2].

The plastics recycling process faces three significant challenges. First, dealing with plastic waste is hugely expensive. Simply removing plastic litter from the United States' west coast costs taxpayers $520 million each year [3]. Effective regeneration techniques are still lacking in current plastic management systems. While the plastics generation increases every year, it leads to an imbalance between input and output. Secondly, combustion and discarding have severe negative impacts on the environment. The degrading process is slow, and toxic greenhouse gases are produced. Plastics waste breaking into smaller pieces, known as microplastics, can adhere to waterborne organic pollutants and infiltrate food webs [4]. Thirdly, due to the outbreak of COVID-19, the consumption and demand for plastics have increased sharply [5]. One hundred twenty-nine billion face masks and 65 billion gloves are used with a monthly estimate [6]. The increasing demand and use of plastics cause significant problems in the plastic waste management system [2]. Many recycling facilities' safety-related suspensions further exacerbate this trend. Without proper public waste management, there is a risk of widespread environmental contamination [6].

The current plastic waste management system needs better approaches to deal with these large numbers of post-consumer plastics. However, it remains unclear what interventions will best support plastic waste management. This paper presents an agent-based model that simulates the plastics waste management lifecycle at multiple scales. Agent-based modeling is a simulation technique that can be used to analyze complex social systems. It is a computational approach that agents with specific variables, behaviors, and characteristics interact with each other [7]. This modeling and simulation provide a direct and visual approach to modeling different scenarios in the current plastics waste lifecycle. Our research question for this study is the following:

R.Q.: How do strategies, such as an education campaign and a system-wide improvement, influence the behavior of plastics waste management?

The paper is structured as follows: Section 2 reviews related background in plastics waste management. Section 3 outlines the research methodology. The research results and recommendations are shown in section 4, followed by a conclusion in Section 5.

II. BACKGROUND

In this section, we will review tthe plastics waste management framework, the classification of recyclable plastics and non-recyclable plastics, and the introduction of Agent-Based Modeling.

A. *Plastics Waste Management Framework*

Plastics' low cost, lightweight, and versatility have a vast area of use in industries. Furthermore, plastic materials usually have ecological and economic advantages over conventional materials throughout their life cycle, with or without considering the End-of-Life stage [8]. Unfortunately, more than half of all plastics end up in landfills, and only 9% of used plastic can be recycled [9]. Additionally, a given plastic piece can only be recycled 2 to 3 times on average [10]. Despite its limitations, recycling remains the best solution for processing plastic waste due to its beneficial economic and environmental impacts. The requirements for successful plastic recycling include proper infrastructure to collect the waste, available technology to reprocess the waste into secondary products economically, and develop markets for the cost-effective use of recycled products [11].

B. *Recyclable Plastics and non-recyclable plastics*

Recycling is the process of converting waste materials into new materials. However, research shows that impurities take up to 28% of plastic waste and that around 75% of plastics waste is considered as Low-Quality applications [12]. The study indicates that although varying between polymer types, the recyclability of "Low-Quality" plastic waste is 12% to 35% lower than those categorized as "high-quality" plastics waste. Therefore, plastics have different recyclability depending on polymer types, legislative requirements, product lifetime, and other variables. Recyclable plastics are clean bottles and containers, bags, etc. As contamination in recycling has many negative effects, such as recycling becomes more expensive as money and time are required to separate contaminants [13][14]. In addition, the quality of recyclable by-products decreases if contaminated, reducing the market value [15]. In other words, if the plastic wastes are contaminated, they will not be considered 'recyclable' anymore. Therefore, the recycling systems are in need of cleaner recycling.

C. *Agent-Based Modeling and its Applications in Recycling*

Agent-Based Modeling and Simulation (ABMS) is the approach used for the development of the model. ABMS is a computational modeling approach centered around the concept of to the term "agent" to describe complex processes, behavior, and phenomena [23]. Unlike other conventional modeling tools, agent-based modeling responds to the environment actively [24]. Certain properties and attributes are autonomous and self-directed, modular, social and interactable, living in an environment capable of learning and adapting, and having explicit goals and resource variables [25].

A popular ABMS technology extensively used in education and research on human behavior is NetLogo [26][27]. NetLogo, a multi-agent and modeling environment, can simulate natural and social phenomena. It allows users to alter the agents and environment to observe the differences directly. It is also well suited for modeling a system that needs a few years to evolve and change [28]. Four types of agents existed in NetLogo are turtles, patches, links, and observer [26]. Turtles are active agents that can move inside the environment. It can perform the programmed functions during the 'turtles' movement and reflect correlative interactions between other turtles and agents. The patch is the square ground where turtles can move on, the links connect two turtles, and the observer is the agent who observes the simulated world and acts as the interface between it and the researcher [29].

ABMS has also been used to study recycling behaviors. For instance, a study conducted in 2018 discovered behavior changes in post-consumer recycling through an agent-based modeling approach [30]. The simulation was applied to analyze the impact of critical factors in recycling behavior changes in Beijing's residential community. The experiment showed that the provision of recycling facilities could cause little change in 'residents' behavior. However, face-to-face interactions between the experiment team and participating households increased awareness of plastic recycling.

III. RESEARCH METHOD

As the plastic waste lifecycle's detailed investigation can be time-consuming and expensive, NetLogo may be an efficient tool to estimate one action's outcomes. Once an ABMS has been built, the user can change multiple parameters manually to simulate a given environment's plastics recycling process through an open user interface. The proposed system zooms in the life cycle of the general plastics waste. Three kinds of turtles were created: Plastics (plastics wastes), Center (recycling centers), and Houses (the number of households in a community).

A. *Definition of the Variables*

Variables shown in Table 1 were created in order to record the interaction of different turtles and the value changes, some variables were created to keep track of the progress and trigger different behaviors. Table I demonstrates the simulation variables with corresponding explanations and justifications for use.

TABLE I. VARIABLES USED IN THE NETLOGO MODEL

Variables		
	Data type	***Explanation***
initial-houses	Integer [0, n]	The number of households created in the environment
recycle-approach	String: Chemical or Mechanical	The most common approach that the recycling facility uses in the simulated environment
RecyclingParticipation	Integer [0, 1000]	The percentage of households that recycle. The variable is internally expressed as an integer

Variables		
	Data type	***Explanation***
		from 0 to 1000 in the program, and then divided by 10 to show the percentage with 1 decimal place
contamination_rate	Float [0, 1]	The percentage of plastic waste that is contaminated
recyclability	Float [0, 1]	The possibility of plastic waste to be considered as recyclable
Demand	Integer [0, n]	The average number of plastic wastes (in kg) generated by the houses weekly
ptime	Integer [0, n]	The number of times the plastic waste has been recycled in the system
landfill	Integer [0, n]	The amount of plastic waste (in kg) is ended up in a landfill.
finish_recycle	Integer [0, n]	The amount of plastic waste (in kg) has been sent to the recycling center and has been recycled in the system
totalplastics	Integer [0, n]	The total amount of plastic waste (in kg) that are generated in the system
collect	Integer [0, n]	The amount of plastic waste (in kg) has been sent to the recycling center
new	Integer [0, n]	The amount of plastic waste (in kg) becomes secondary products

B. The Simulation Workflow

The process starts when the houses use plastics based on their weekly demand (variable demand). Then, the system checks the household's recycling participation percentage (variable RecyclingParticipation) to see if the house will decide to recycle the plastic waste. If the household does not plan to do the recycling action, all plastic waste generated from the house will go into landfills. In contrast, the households that choose to perform the recycling action send the plastics to the recycling center. When the plastic wastes arrive at the recycling center, the center will check for the contamination rate (variable contamination_rate) of the collected plastics (variable collect). Only the plastics that are considered as uncontaminated can continue the process and check for their plastics recyclability (variable recyclability), while the "dirty" plastics will be sent to landfills. If the plastic waste is non-recyclable plastic, it will go into a landfill. The recycling center checks its recycling approach (variable recycle-approach) for the rest of the plastics. If the center applies a chemical recycling approach, the plastic waste will be converted to secondary products (variable new). In the case the center uses the mechanical recycling process, the plastic waste will be recycled with an increment in the number of times the plastics have been recycled in the system (variable ptime). Plastic waste that exceeds the recycled time will be downcycled and will disappear in the system. Eventually, the recycled plastics that are shipped back to the community will satisfy households' needs and reduce their next cycle consumption. The user interface is shown in Figure 1.

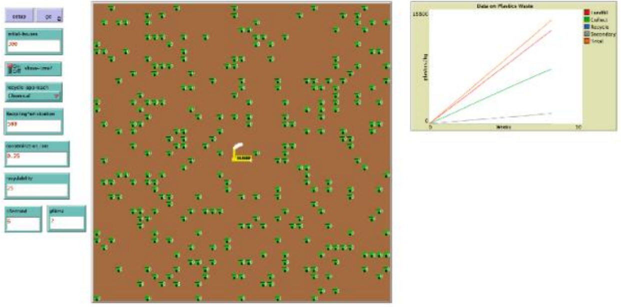

Figure 1. The Screenshot of the simulation interface.

During the simulation running, graphic charts track the variables to support the calculations, named "Data on Plastics Waste." Figure 2 provides the methodological framework used in the simulation.

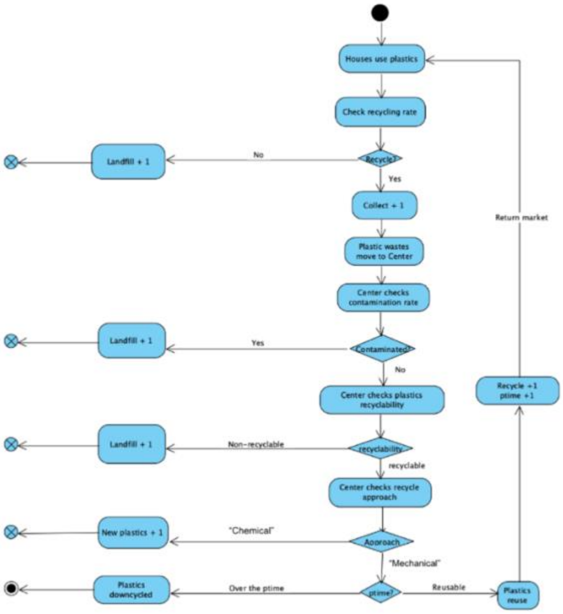

Figure 2. Simulator methodology framework.

A software tool named BehaviorSpace, which is part of NetLogo, allows us to test each scenario for ten repetitions and calculate the overall mean and standard deviation.

IV. SIMULATION EXPERIMENTS AND RESULTS

To test the feasibility of the simulator, we applies real-world paramenters to the simulation. A baseline scenario is constructed to demonstrate the effect of the education campaign and system-wide improvement. All the results are collected from 10 repetition run simulating the activities in 25 weeks.

A. *Feasibility Testing*

According to the American Chemistry Council and the National Association for PET Container Resources, in 2018, (1) 35,680 thousand tons of plastics waste were generated, (2) 5,620 thousand tons of plastics waste were combusted with energy recovery, (3) 3,090 thousand tons of plastics waste were recycled, and (4) the rest of 26,970 thousand tons of plastics waste ended up in landfills. Then, the recycling rate of 2018 plastics waste was 8.66%. On average, 25% of collected wastes are contaminated to be recycled [22]. If we assumed that all non-recyclable plastics would be incinerated, and 25% of the collected plastics went to landfill. Also, the sum of collected plastics in 2018 would be 11613 thousand tons, with a 32.55% recycling participation rate (collected plastics/total generated plastics) and 35.48% of recyclable plastics rate (recycled plastics/non-recyclable plastics). Based on The Guardian, the U.S. produces about 106.2 kg of plastics waste per person per year [32]. The weekly consumption per person would be 2.04 kg (106.2 kg/52 weeks). Applying these parameters in the simulation, the average recycling rate is 8.97% for ten weeks run, and this result has less than 0.5% difference with the PET Container Resources data in 2018.

B. *Baseline Scenario*

Based on the nationwide parameters and literature review, we constructed a baseline situation in our model. The baseline Scenario simulates 500 households, with the recycling participation of 25%, plastics recyclability of 25%, and uses a mechanical approach. The maximum time that plastic waste could be reused was set to 2, and the average plastics consumption per household was 6 kg/week. Therefore, a fixed 25 percent contamination rate is applied in the baseline scenario and the rest of the experiments. Because the number of turtles needs to be positive integers, the parameters used to generate turtles were rounded up to whole numbers. This simulation scenario was acted as a 'baseline' to evaluate the effect of customer behavior changes or system-level improvements. The results of the baseline scenario are included in Figure 3.

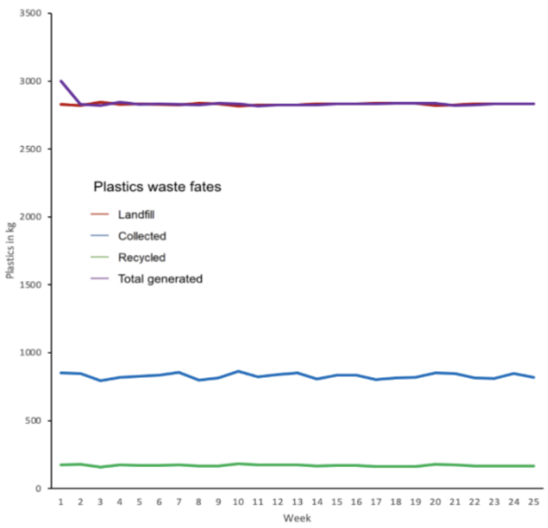

Figure 3. Baseline testing of plastics waste management over 25 weeks.

C. *Effect of an Education Campaign*

Plastics Recyclability is the percentage of plastics considered "recyclable" when they arrive at the recycling center. Recycling participation refers to the tendency of each household to recycle weekly. Two possible reasons that cause the plastics waste unrecyclable are: there are no facilities supporting recycling for the specific type of plastics, and the plastics are contaminated during transportation or without improper recycling procedures. In this paper, we have a fixed contamination rate of 25% applied to all collected plastics, so the recyclability of the plastic here will only examine the plastic types.

Education can make more people decide to recycle, or it can make them recycle more effectively and adequately. In this experiment, we tested the effect of an education campaign that produces individual improvement in recycling participation or plastics recyclability. We looked at the effect of 5%, 10%, 25%, and 50% improvements on plastics recyclability and recycling participation from our baseline, reflecting the increased sorting and recycling behaviors. The results, which are compared to the baseline testing, are shown in Figure 4.

D. *Experiment 2: Effect of System-wide Improvement*

This experiment examined potential system-wide improvement based on technological changes, infrastructure investments, or policy implementation that may boost recycling participation and plastics recyclability. Unlike education campaigns, system-wide improvements significantly improve waste management, such as California's single-use plastic bags ban [35]. Improved recycling infrastructure can handle a broader set of plastics. We tested the plastics recyclability and recycling participation scenarios when they were 50%, 75%, and 100% (Hypothetical maximum), and the results are shown in Figure 5.

Similar to the education campaign, higher plastics recyclability and higher recycling participation can lead to larger recycled plastics amounts, lower landfill deposits, and lower total plastics. Compared to plastics recyclability, recycling participation creates a slightly stable percentage increase in recycled plastics and percentage deduction in landfill deposits and total plastics. Especially in boosting the recycling participation, recycled plastics follow a similar increase proportion every week as the percentage increases. Therefore, we could predict that if the government considers investing in the system-wide development in its plastics waste to raise its recycling rate, increasing recycling participation may lead to a stable boosting in the recycling rate over weeks while increasing the recyclable plastics have more variations each week. Moreover, in this experiment, 100% improvement is a test of hypothetical boundary conditions. The result shows that there remains a significant landfill problem even in a hypothetical scenario with recycling participation.

V. CONCLUSION

The results of the feasibility testing of nationwide data support that the simulator developed in this paper can be a way to predict the plastic waste trend. This study's main conclusion was that approaching this system-level problem in a one-dimensional way is insufficient. Simply altering individual behaviors through education has limited effects on the system. Similarly, solely examining the technology development in both system-wide improvements has limited effects. Education, technology, and infrastructure changes should all be carried out to ameliorate the plastics waste management problem. Nevertheless, promulgating a policy or developing an advanced technology is not easy; before a system-wide improvement takes place, individual behavior change still affects the recycling rate to a certain degree.

There are still some limitations and shortcomings in the present study. First, the plastics recycling approach was mainly based on plastic types. The simulation assumes all plastics categorized as recyclable can undergo both mechanical and chemical processes. Second, recycle participation can be a subjective factor and hard to record. Third, household amount limitation restricted the simulation's scope, which can only simulate a community's small region. Fourth, the incineration process was not considered in the simulator. Despite its limitations, the study combined the plastics waste management life cycle and computer technology to test various scenarios and predict possible outcomes. Further research is needed to consider the plastic types and test out the effect of the combination of education, technology, and infrastructure improvements in the system.

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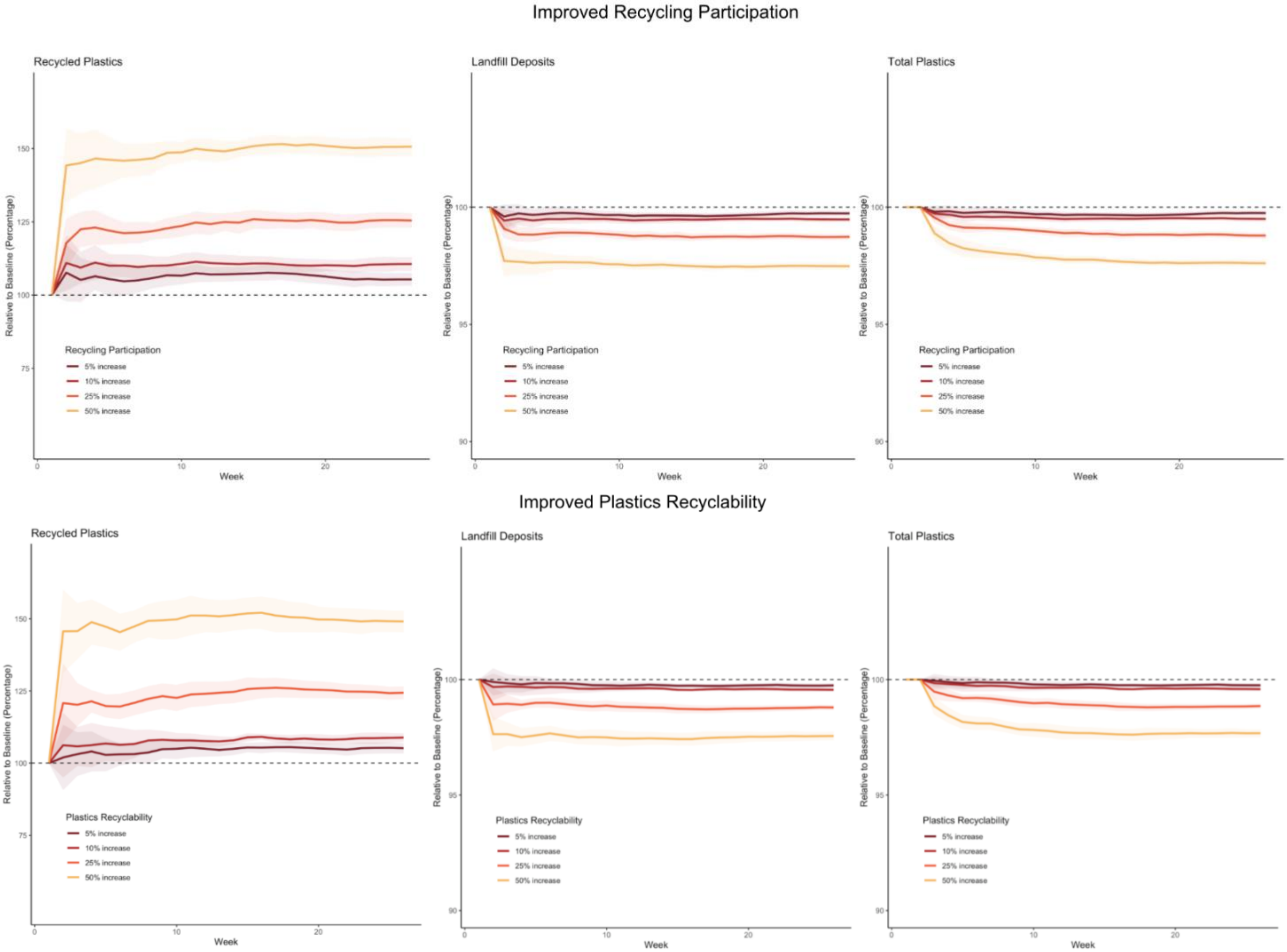

Figure 4. The effect of education campaign over 25 weeks.

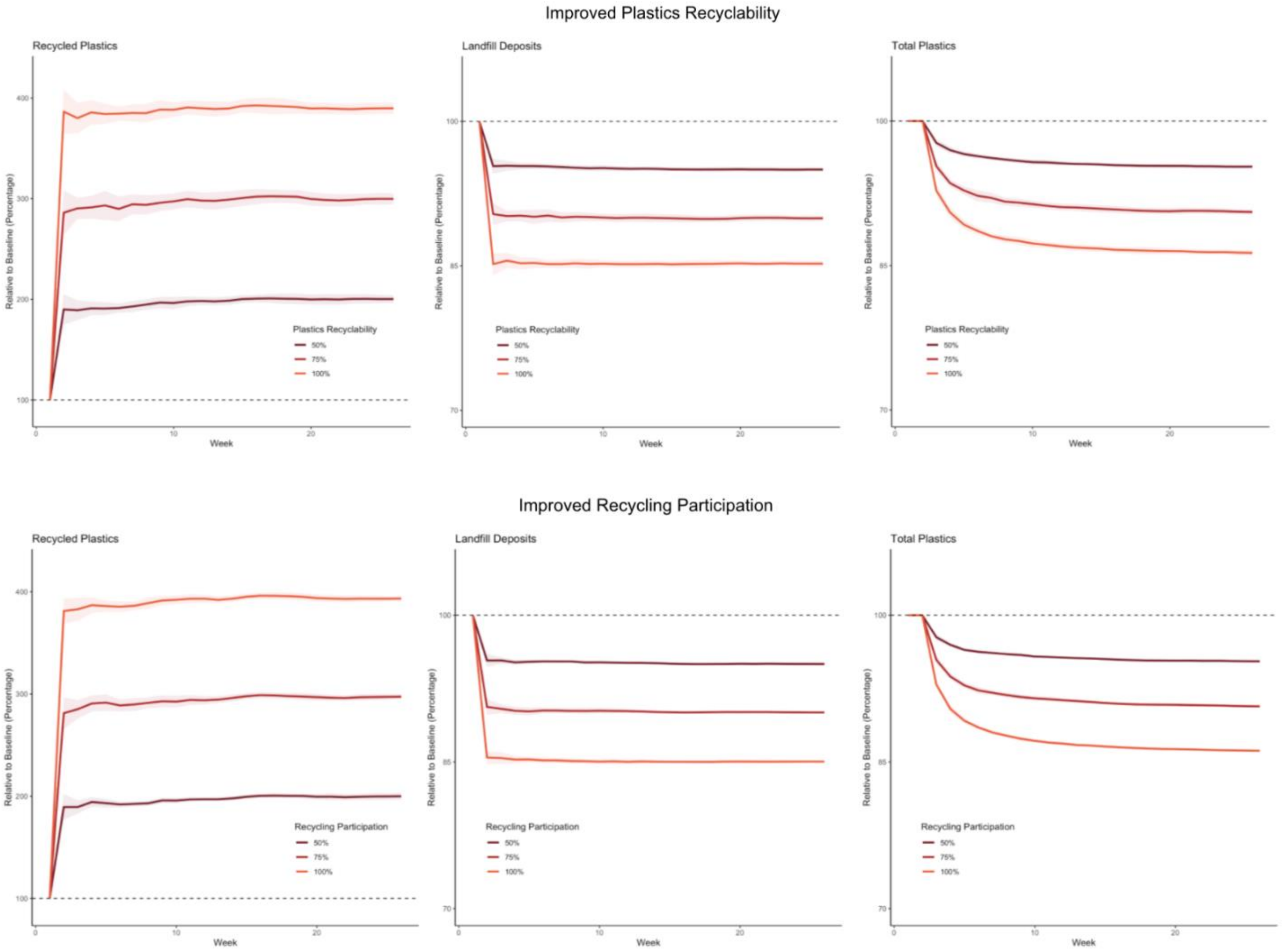

Figure 5. The effect of system-wide improvement over 25 weeks.