Waste Not, Want Not: Putting Recyclables in Their Place

Advice to the EPA for National Recycling Regulations: A Study of National Plastic Use Projected for the Next Decade and a Comparative Analysis of Three Methods of Recycling for Three Cities

Team #1851

Executive Summary

The hot-button issue of our modern era is attempting to prevent the rapid decline of the environment due to human activity. Perhaps the most advertised method of "being green" is recycling, which is the conversion of waste into a reusable material. However, common methods for recycling at the local, state, and national levels are often underused and inefficient. Our overall task is to analyze the cost vs. benefits of recycling by evaluating multiple defined methods in the context of certain cities and then extrapolating that information to the national level.

The first step was to create a picture of where America is right now in terms of plastic waste and landfill usage, and then project that growth rate for the next ten years. We created one model relating national population growth with respect to time and another model relating national plastic waste with respect to time in order to account for changes in both population and plastic waste generation. We united the two models by creating a ratio of pounds of plastic waste per person for each year, which averaged to 224 lbs./person with the ratio value increasing over the next decade. According to our data, the amount of plastic waste generated over the next ten years is 365 million tons, and the amount of plastic waste that will be in an American landfill ranges from 141 to 149 million tons, with the variation due to potential behavior changes in recycling habits.

The second step was to evaluate three methods of recycling (described further below). We chose to define the best method as the one which produces the most favorable ratio of environmental benefit in metric tons of carbon emissions saved to cost in 2013 U.S. dollars. The cost was created as a function of creating and maintaining the recycling plant as well as transportation of recycled materials. This definition is more useful than a simple cost analysis because it does account for the environmental benefits. Next, the models for each of the three methods were applied to the following three cities: Fargo, North Dakota; Price, Utah; and Wichita, Kansas.

Our results showed that there was no one best method. Method 1, which involves drop-off locations, produced the most favorable carbon expense ratio for Price, Utah, at a value of .005 tons of carbon saved per dollar. However, Method 3, which proposes curbside pickup with a garbage tax on each bag of non-recycled material placed on the curb, produced the most favorable ratio for Fargo, North Dakota, and Wichita, Kansas, with ratios of .121 metric tons of carbon emissions per dollar and .411 metric tons of carbon emissions per dollar, respectively. An analysis of Method 2 did not yield any favorable results.

Due to the varying results, we advise the EPA to not impose blanket regulations, but rather create intervals of population that would determine which method should be used. Areas with low populations such as Price, Utah, should only have a recycling drop-off system, while cities above a certain population, such as Fargo and Wichita, should be required to have single-stream curbside pickup with a garbage tax. However, a garbage tax—in essence, an incentive to recycle—will increase recycling in all areas regardless of the population of that area, so the EPA could implement that tax across all systems. Therefore, the best way for the EPA to enforce optimal recycling habits in the different regions of the United States is to require these local governments to look into the many options available, and then choose the one that gives them the largest ratio of carbon emissions diverted to government dollar.

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Background Information

Not until recently has there been a serious push for our society to recycle. In the 1950s, recycling was virtually unheard of as landfills seemed limitless, but in the 1960s and 1970s began a movement to conserve, and to bring a halt to what seemed like a frenzy of waste.

Now that the United States is aware of various frightening scientific phenomena such as the landfill gas released by slowly photodegrading plastic and other waste (ICF 4), the pollution of the environment by our waste and the chemicals used to process it, and the increasing cost of harvesting new and virgin natural resources, efforts to stop our country's large scale consumption and disposal of new resources has redoubled on its political, scientific, and economic fronts.

Towns started off by offering one or more drop-off sites for those who were willing to organize their waste products and deliver them to a central location. Reasoning tells us that people who are not heavily motivated to recycle will not drive very far with trash in their cars, so logically this system seems best suited for a small town locale, where bringing trash to a drop-off site is not a burden. Our data reflect this, in that the town of Price, Utah, has a higher ratio of amount of carbon conserved per dollar spent than the other, larger, towns, under this same system of operation.

When the idea of trash trucks spread to recycling trucks and curbside pickups of recyclable goods became a common concept, people became much more willing to recycle. Naturally, the simplicity of having such a huge impact on the environment and economy merely by sorting through your trash for reusable materials and putting them out by the curb brought more people into the world of recycling, but the costs associated with paying staff to separate the materials into their individual types for processing casts the economic viability of this system into pragmatic doubt, and detailed analysis of the environmental impact and profit from selling the refined materials is necessary. Government encouragement of recycling through a system of "pay as you throw"–a government-imposed tax or fine on garbage collection on a volume basis (like water or electricity) as opposed to the traditional flat fee of collection–aims to dissuade citizens from wantonly disposing of their belongings, serving as the proverbial stick to accompany the carrot of easy, curbside disposal of recyclable goods. "Pay as you throw" already has a foothold: almost 10% of Americans live in a community where this system has been implemented (Folz & Giles, 3). As might be expected, this system is more viable on a larger economy of scale, when paying for trucks and sorting staff becomes marginal and the sale of recycled materials is enough to cover it.

Information on Tested Cities

Fargo, North Dakota
With a population of 105,549 people, Fargo is the largest city in North Dakota, and that population is growing steadily (City of Fargo 1). Yet despite a relatively large population, Fargo was ranked first in urban environmental efficiency out of an evaluation of 72 cities by the Earth Day Network, hosting a landfill gas-collecting plant that converts degrading waste to fuel (1). From a geographical perspective, Fargo is surrounded by open and flat terrain (2). According to the City of Fargo's website, Fargo offers free curbside recycling for residents along with 27 drop-off locations throughout Fargo for the collection of recyclables (4).

Price, Utah
Price, Utah, has a population of 8,682 people, and that population is declining at a negligible rate (Census Quick Facts 1). Price has no current curbside recycling system; however, Price features several drop-off recycling locations (1 Price City Utah). From a geographical perspective, Price resides on the northwestern edge of the Colorado Plateau (2).

Wichita, Kansas
According the U.S. Census Bureau, Wichita, on the border of the Arkansas River, has the largest population of the three cities, with a current population of 384,445 people (2010 U.S. Census). Wichita has both a drop-off and a curbside recycling system as well as a system where consumers are paid to recycle. Geographically, Wichita features a vast range of temperatures and precipitation levels (Census Quick Facts 2).

Information on Tested Methods

Method 1: Drop-Off
In this method, people drop off pre-sorted recycled materials to given drop-off locations in their local area. This is the lowest cost method of all the tested methods because the transportation costs are borne by the individual rather than the recycling company. Furthermore, the aggregate cost of maintaining the drop-off locations is near zero because the drop-off locations are embedded into existing systems—i.e., parts of stores and township buildings. In our analysis, this method is assigned the variable J_D.

Method 2: Single-Stream Curbside
In this method, recycled materials are picked up from the curb of people's homes. While this method may be the most convenient for consumers, it represents the greatest cost for the recycling company. In our analysis, this method is assigned the variable J_S.

Method 3: Single-Stream Curbside with Trash Tax
Although this method has the same pickup plan as Method 2, it includes an incentive for people to recycle more by charging a tax for every bag of non-recycled waste put on the curb. This tax aims to reduce the amount of recyclable goods that are trashed, not recycled. In our analysis, this method is assigned the variable J_T.

Restatement of Problem and an Analysis of Its Implications

Plastic is often lauded as inexpensive and durable, enabling a diverse array of products from cell phones to artificial limbs to be manufactured more cheaply. However, due to inefficient and underused recycling methods, the modern era's increase in plastics usage has paralleled the decline of the environment. The consumer use of plastic has created massive landfills and ocean dumps, which results in increased carbon dioxide emissions, decreased land availability, and general decrease in the quality of all forms of life.

The first task is to create a model for the amount of plastic in landfills in the United States, and then project the findings to determine the amount of plastic in landfills over the next ten years. Because plastics do not biodegrade within a decade, the total amount of plastic is summative, thereby resulting in an approximately tenfold increase of plastic in landfills. As a result, it is critical to decrease the amount of plastic being sent to landfills. The most environmentally friendly way of doing so is through increased recycling of waste plastics.

Our second task was to evaluate the potential recycling methods for all materials. Because our model was developed independent of existing recycling practices, we factored in the cost of building a new recycling plant, the operating cost, and the cost of transportation of materials to the plant. Conversely, we also factored in the potential revenue of selling the processed recycled materials. However, the measure of merit for each recycling method is not purely economic; we quantified the environmental benefit of each method by estimating the metric tons of carbon emissions not released into the atmosphere. We evaluated the following methods of collecting materials to be recycled:

1. **providing locations where one can drop off pre-sorted recyclables**
2. **providing single-stream curbside recycling**
3. **providing single-stream curbside recycling in addition to having residents pay for each container of garbage collected**

These specific methods will provide an accurate picture of the feasibility of broader recycling feasibility because the above methods run the gamut of amount of individual participation required and evaluating the feasibility of enforcing disincentive for not recycling.

We evaluated our methods in the context of implementing these systems in the following cities:

1. **Fargo, North Dakota**
2. **Price, Utah**
3. **Wichita, Kansas**

An analysis of the above cities will lend itself well to extrapolation to the national level because the above cities have vastly varying populations and geographic locations, which is thereby more representative. The third task is to **consider the national implications of the results of our study in order to advise the EPA on recycling guides and standards to implement on all states and townships in the United States.**

General Assumptions of Our Model

Population Growth

Because we modeled current population and growth rate off of U.S. Census data, we set $t_0 = 2010$ CE. We assumed that the rate of population growth will remain constant over the next ten years. This assumption is justified because the model is used to project the United States population for a relatively narrow window of time. We also assumed that there would be no “population shocks”—that no natural disasters or diseases would drastically affect the population growth rate.

Amount of Plastic Waste

We modeled the rate of change in the amount of plastic waste generated per year based on the percent growth of the national manufacturing industry. We are justified in making this assumption because plastics are a critical part of the manufacturing industry, so their growth rates would be similar. Furthermore, we assumed that there would be no major economic crises that would affect the plastics industry.

Recycling Methods

While we described the general recycling systems of each city, we developed models for each method in each city independent of existing recycling infrastructure.

We also assumed that because Method 1 and Method 2 both contain no incentive to increase or decrease recycling, people would contribute the same amount of recycled material under each methods.

Individual Cities

We assumed that the prevalence of a culture of "green" technology, as in how willing people are to recycle, is constant throughout the nation and will not change significantly in the next decade unless otherwise specified.

Environmental Benefit of Recycling

In order to predict the environmental benefit of recycling, we created a model relating the amount of materials recycled to the resulting decrease in the amount of carbon emissions into the atmosphere. We assumed that the reduction of carbon emissions will be the only significant environmental benefit of recycling.

Part 1: Production Rate of Plastic Waste

The key variables in modeling the production rate of plastic waste over the next ten years per person are population, or the number of people using plastic, and the rate of growth of the plastics industry. The latter variable is needed because we assumed that if the national plastic industry is growing, plastics consumption, and therefore waste, is also growing at about the same rate, as supply will naturally increase with demand. We decided to find a per capita plastic waste for each year over the next decade in order to later apply that ratio to the population of individual cities

Population Growth of United States

Assuming that the rate of growth in population will remain about constant throughout the next ten years, the United States' rate of growth is .73% per year with a current population of 315.1 million (Bass 1). Because the projection is only for the next 10 years, an unbounded population growth model can be used. Thus the rate of growth can be given by the following differential equation:

$$\frac{dP}{dt} = .0073P\ .$$

Integrating and exponentiation this equation yields the following model for U.S. population in millions of people with respect to time:

$$P = 315.1e^{.0073t}\ .$$

While this model is not sensitive to minor changes in the rate of population growth, the function is useful in providing a general estimate of U.S. population over the next ten years.

Definition of Plastic Waste

We defined plastic waste as plastic that is collectively disposed of by the United States every year due to consumer and industrial use—this includes plastic meant for landfills, incineration, ocean dumps, and recycling. We included all methods of deposing of plastic in order to later account for the costs of each. Plastic waste includes plastic originating from durable goods, non-durable goods, and container goods.

The amount of plastic waste disposed of by the United States is in 2010 is 31.04 million tons (2010 EPA Fact and Figure Sheet 5).

Production Rate of Plastic Waste

Assuming that general consumer and industrial behavior remains constant, the production of plastic waste will increase with the predicted population growth rate. As the United States becomes more populated, more plastic waste will be generated. Because the plastics industry is so intrinsic to modern manufacturing, the value of aggregate growth in the manufacturing industry can be applied to the growth of the plastics industry. Therefore, the average growth of the plastics industry can be estimated at 3.5% per year (Schantz-Feld 1). With the initial amount of plastic waste disposed of by the United States at 31.04 million tons, or 62080 million pounds, the amount of plastic waste generated by the United States per year in millions of pounds as a function of time adjusted for growth rate is given by:

$$W(t) = 62080e^{.035t}\ .$$

While this model is not sensitive to changes in the rate of growth in the plastics industry, the function is useful in providing a general estimate of plastic waste in the United States over the next ten years. There is an intrinsic uncertainty in this model due to the unforeseeable potential for technological advancement in materials science and consumer behavior; however, it is necessary to create a baseline value for plastic waste per year.

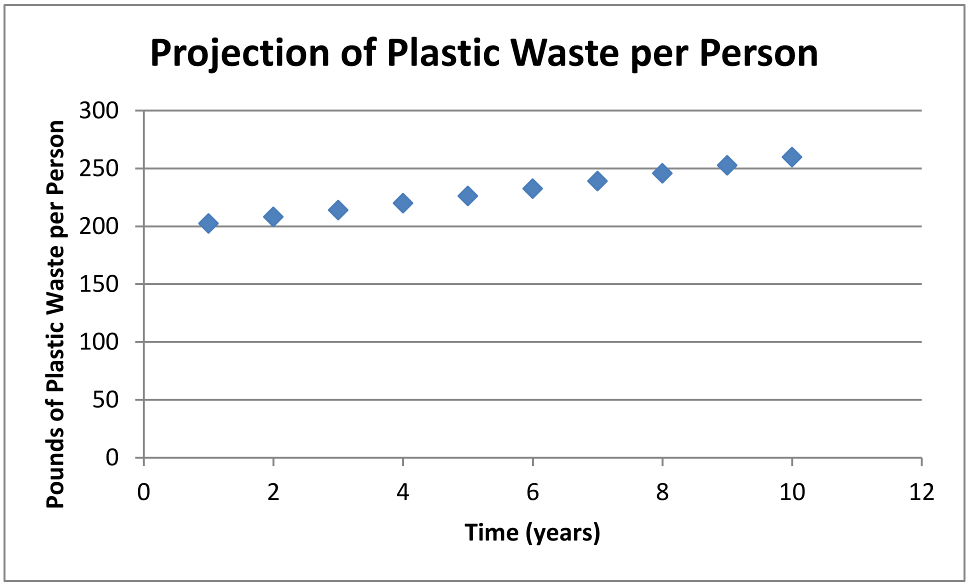
Production Rate of Plastic Waste as a Function of a Changing Population

A model predicting only waste as a function of time would not account for changes in population; conversely, a model predicting population as a function of time multiplied by a baseline value for plastic waste will not account for predicted growth in the plastics industry. Ergo, the two functions must be united to produce a function relating average waste per person per year. The table below shows the pounds of waste per person for the next ten years.

Table 1: Production Rate of Plastic Waste over Time Adjusted by Changes in Plastics Industry and Changes in Population

Year(t) Year 0=2010 CE	Total Plastic Waste in millions of pounds (W)	Total Population in millions of people (P)	Plastic Waste Per Person in pounds per person (W/P)
0	62080	315.1	197.02
1	64291	317.41	202.55
2	66581	319.73	208.24
3	68953	322.08	214.09
4	71409	324.44	220.1
5	73953	326.81	226.28
6	76587	329.21	232.64
7	79315	331.62	239.17
8	82140	334.05	245.89
9	85066	336.5	252.8

Graph 1:



The above data have a great degree of accuracy and flexibility in estimating the ratio of waste to population because it accounts for changes in two variables, population and the plastics industry, rather than holding one as constant. Furthermore, this method of ratio analysis does not impose a linear increase on the rate of growth of the waste per person.

Amount of Plastic Waste in Landfills in the Next Ten Years

General Model

We are assuming that the only way the amount of plastic in landfills will be reduced is if that plastic material biodegrades. At minimum, plastic materials take 100 years to completely biodegrade, and plastics made with polyethylene terephthalate will never biodegrade (O'Connor 1). As a result, it is safe to assume that all plastic placed in a landfill since the onset of massive plastic production about 50 years ago is still there and has not biodegraded nor will it in the next ten years. Thus, plastic waste in landfills can be given by the following, where L represents total amount of plastic waste by 2020 in pounds, L_o represents the amount of plastic waste already in the landfill, and L_{10} represents the amount of plastic waste that will be added in the next 10 years:

$$L = L_o + L_{10\,.}$$

The initial weight in 2010 of all plastic in American landfills is 32 million tons, or 64 billion pounds (Killam 1).

Amount of Plastic Added to Landfills in the Next Ten Years

The current percent of plastic waste sent to landfills is 32% (Discover Magazine 1). However, given the possible implementation of our methods to increase recycling, we must account for the possible decline of waste plastic sent to landfills. We are assuming that due to the general efforts to promote environmental protection, the current percent of waste plastic sent to landfills will not increase.

According to the Association of Postconsumer Plastic Recyclers (APR) and the American Chemistry Council (ACC), plastic bottle recycling by consumers increased by 5% in 2010 (2010 PET and Bottle Rate Reports 1). While this number does not apply to all plastics, we created the constant Q to represent the percent increase in the amount of plastics being recycled. Therefore the model predicting the total amount of plastic waste is given by the following using plastic waste data per year from Table 1:

$$L = L_0 + .32(1 - Q)\sum_{t=0}^{9} W(t)\,.$$

Setting $Q = 0$, meaning no decline from current percent of plastic waste sent to landfills, yields a total value of 297,720 million pounds of plastic in American landfills in 2020, or 149 million tons. Setting $Q = .05$, meaning a 5% increase in aggregate plastics recycling, will yield a value of 282,834 million pounds of plastic in American landfills in 2020, or 141 million tons.

By creating a value of Q, this model becomes sensitive to behavioral changes among consumers as well as the potential explorations of other disposal techniques.

Part 2: Designing Models for Each Method of Recycling

We designed several mathematical models that would predict the net profit for each given type of recycling method based upon the region it serves and the specific year data for which it was desired.

Profit Analysis for Various Recycling Plants

Profit of a Single-Stream Recycling Plant

Our model for the construction and running cost of a pickup single-stream recycling plant (J_S) (Method 2) is given by

$$J_S(t) = M(t) * (R - Z) - H(t) * V \ ,$$

where t is the number of years after the initial year, 2010, of which profit will be analyzed. For example, $J_S(3)$ will give the profit in the third year of operation, 2013. $M(t)$ represents the tons of recyclable material processed by a plant per year and will be defined in detail later. $H(t)$ represents the households in the area in a given year, and will be defined with $M(t)$. R is revenue created per ton of processed material, Z is the processing cost for each ton of recyclable waste, and V is constant transportation cost per household for collecting recycled waste. For V, we used the average trash collection cost per household for a once-a-week set out collection, which turned out to be $54.40 per household (EPA-Collection 1). We are assuming the cost for the multiple trips required to collect waste in a denser area, such as a city, counteract the advantages of the close proximity of the number of households, meaning transportation cost, $H(t) * V$, will vary linearly against $H(t)$ for increasing values of $H(t)$.

Quantity of Material Recycled by Each Plant

Assumptions:

- Though we realize recycling trends may change, we are assuming the same ratio of recycled waste to total waste produced will remain constant in the near future.
- We are also assuming the rate of growth for each city analyzed is consistent with the Census Bureau's past data for growth rate and will not change drastically in the near future.
- We are assuming that the number of persons per household will also remain constant.

$M(t)$, the tons of material processed, is determined based upon the number of households in the area that the plant is responsible for, represented by $H(t)$. For each city, using data from the 2010 census (2010 Census), $H(t)$ is given by

$$H(t) = \ H_0 * (1 + k)^t \ .$$

H_0 is also given by $H(0)$ and represents the number of households in the 2010 census, from which we have taken our data. k is assumed to be constant and is the population growth rate for that region. t is the number year after the 2010 census for which we are analyzing data. For example, $H(4)$ is the household amount for that region in 2014. $M(t)$ is then given by

$$M(t) = H(T) * P_H * M_P ,$$

where H is households in the area, P_H is the average persons for household for that area, and M_P is average tons of recycled waste produced per person. P_H is taken from the 2010 census for each city specified. M_P is constant and is 0.2755 average tons of recycled waste produced per person per year. This is calculated from the average amount of 1.51 pounds of recycled waste per person per day (EPA-Waste). Thus, assuming constant regional growth and a constant household to population ratio, $M(t)$ gives the tons of material processed by a plant for one region for t years after 2010, and $H(t)$ gives a household amount for a region for t years after 2010.

Processing and Revenue of a Single-Stream Recycling Plant

Assumptions:

- We are assuming that most recycling plants operate with the same methods and average cost as the two plants we analyzed. We used this data due to scarcity of information for other plants and their operating costs and revenues.
- We are assuming the changing market rates for the recycled material will not significantly change the yearly revenue for sold recycled waste.

In our initial equation, Z is the cost of the plant to process a ton of material and was derived and averaged from data for two recycling plants—one in Susquehanna County (Susquehanna report) and the other in Wayne County (Wayne Report)—for the year 2005. The yearly cost of each plant to process a ton of material was derived by dividing the yearly cost to run the plant by the tons of waste processed per year. For Wayne County's recycling plant, this was given by $99.4 per ton per year, which is $298,373 per year (Wayne Report 5-1) divided by 3003.2 tons processed (Wayne 2-17). For Susquehanna, this was given by $126.2 per ton per year, which is $267,991 per year (Susquehanna Report 5-1) divided by 2,124 tons processed per year (Susquehanna Report 2-19). Z was then calculated by averaging the processing cost of each plant, which turned out to be $112.76 per ton processed. R, in our initial equation, is the revenue generated per ton of processed material. This was, like Z, averaged from each report by the ratio of revenue generated per year by sold material to the total tons of processed waste per year. For Wayne, this was $59.01 in revenue per ton processed, derived from $117,219 in revenues (Wayne Report 5-3) divided by 3003.2 tons processed. R averaged out to be $48.23 in revenue per ton processed. Thus, MZ represents the processing cost for a variable tonnage of waste per year, and MV represents the revenue generated per variable tonnage of waste per year.

Sorting Cost of a Single-Stream Recycling Plant

Assumptions:

- We are assuming the majority of plants use the same methods and follow the same sorting costs as the Susquehanna County recycling plant.
- The plants we analyzed used prison inmates and community service workers to carry out sorting work. We are assuming the availability of prison laborers and forced work is not

consistent for every city, so we will use Susquehanna County's processing plant's prediction for sorting cost for regular labor to analyze sorting cost of each recycling plant.
- Our model does not account for the changing wages for recycling plant sorting workers.

The Susquehanna County recycling plant uses prison labor and community service work for the majority of its recycling (Susquehanna Report 4-1). They estimate a savings of approximately $45,760 per year at a wage of $7.00 per hour due to their usage of prison inmates (Susquehanna Report 4-1). This, combined with the annualized cost of $6,379 per year for the sorting equipment (Susquehanna Report 5-3), gives a total cost of $52,139 for that year, which, divided by tonnage processed that year, gives us a sorting cost of $24.54 per ton per year.

Construction and Processing Cost of a Pre-Sorted Drop-Off Plant

Our model for construction and running cost of a pre-sorted drop-off recycling plant (J_D) is given by

$$J_D(t) = M(t) * (R - Z_D) .$$

This model is very similar to our model for a single-stream pickup plant except for two main differences. One major difference is that the collection and transportation cost, given by $H(t)V$, is not included in the equation since recyclables are dropped off. The other major difference is Z_D, which will be less than Z. Because we do not have to account for sorting costs in a pre-sorted system, Z_D is given by Z—*sorting cost per ton per year*. Z_D turns out to be $88.22 per ton per year. $M(t)$, tons processed per year, will be the same regardless of processing method and only vary based upon which year is analyzed.

Processing and Revenue of a Single-Stream Recycling Plant with a Garbage Tax

$$J_T(t) = M(t) * (R - Z) - H(t) * V + H(T) * G .$$

$J_T(t)$ represents the profit of a single-stream recycling plant with a garbage tax, with G representing the tax taken in per household per year. We are assuming that a garbage tax similar to past implementations of a garbage tax is used. For the purpose of this investigation, we are also assuming that every house puts out on average one bag of trash per week. We used the past value of $0.80 per garbage can, as was used in Charlottesville, Virginia (Fullerton 1). Therefore, G is given by 52 weeks * $0.80 per week taken in, or $416 of tax per household per year. The rest of the model is identical to $J_S(t)$ since the only change is the addition of a garbage tax.

Overall Profit Model for Each Type of Recycling Plant

All profit models account only for a running cost of a given recycling plant and do not include construction costs.

All projections include predictions for $M(t)$ and $H(t)$, which are given by

$$H(t) = H_0 * (1 + k)^t ,$$

where H_0 is households in the city for the year 2010 and k is the city's population growth rate calculated in the 2010 census.

$$M(t) = H(T) * P_H * M_P \ ,$$

where P_H is given by the average persons per household, which varies per city and is assumed constant, and M_P is assumed constant at 0.2755 average tons of recycled waste produced per person per year.

For **Method 1**, the pre-sorted drop-off method, the plant profit is given by J_D:

$$J_D(t) = \ M(t) * (R - Z_D) \ ,$$

where $M(t)$ is tons of waste recycled per area in a given year, R is the plant's revenue for selling processed material per ton processed, and Z_D is the cost per ton to process pre-sorted material.

For **Method 2**, the single-stream pickup method, the plant profit is given by J_S:

$$J_S(t) = M(t) * (R - Z) - H(t) * V \ ,$$

where $M(t)$ is tons of waste recycled per area in a given year, R is the plant's revenue for selling processed material per ton processed, Z is the cost per ton to process non-sorted material, $H(t)$ is the household amount for a region in a given year, and V is \$54.40 of collection cost per household. $H(t) \ * \ V$ gives total collection cost for a given year.

For **Method 3**, the single-stream pickup method with garbage tax, the plant profit is given by J_T:

$$J_T(t) = M(t) * (R - Z) - H(t) * V + H(T) * 52 \frac{weeks}{year} * \frac{1 \ container \ collected}{house \ week} * \frac{\$0.80}{container \ collected},$$

where $M(t)$ is tons of waste recycled per area in a given year, R is the plant's revenue for selling processed material per ton processed, Z is the cost per ton to process non-sorted material, $H(t)$ is the household amount for a region in a given year, V is \$54.40 of collection cost per household, and G is \$416 per household per year. $G * H(t)$ represents the garbage tax.

Thus, the model relies on and varies with the following independent variables.

P_H: Average number of persons per household for a given area.

k: The population rate of growth for a given area.

H_0: The number of households in an area for the year 2010.

Ultimately, $J(x)$ will give the profit of the plant for the x^{th} year after 2010; i.e., $J(5)$ will give the profit of the plant for 2015, the 5$^{\text{th}}$ year after 2010.

Testing the Model for Each Recycling Method

In testing the methods, the best method is defined as the one which produces the most favorable ratio of environmental benefit in metric tons of carbon emissions saved to cost in 2013 U.S. dollars.

Evaluating the Environmental Impact

As the EPA will naturally assess options based on both cost and environmental impact, it becomes necessary to identify not only the difference in cost which would proceed from each recycling method, but also the difference in environmental impact from a result of each one. A need for a standardized way to measure the difference in environmental impact of any of the methods is provided by the EPA's preferred unit of MTCE, or metric tons of carbon equivalent, a unit which effectively measures the amount of greenhouse gases being released into the environment which is weighted according to the greenhouse potency of each gas. (For instance, an MTCE of methane would be substantially less than a metric ton.) We assumed that each unit of MTCE was equal, and that a higher MTCE level inherently implied a greater degree of environmental degradation/harm, because it is an effective way to standardize greenhouse gas emissions in terms of potency, which is suitable for the scope of this effort, and because the details of climate science are too complex to be accurately analyzed.

Estimates of the MTCE savings for recycling 1 ton of any given substance (i.e., the MTCE's released from adding 1 ton of paper to a landfill, subtracted from those emitted in the recycling process) enabled us to form an estimate of the MTCE savings per ton of recycling 1 "average" ton of waste material (X) (a ton of waste which is representative, percentage-wise, of the total waste materials generated in one year). The MCTE savings for recycling 1 ton of a given substance, represented by variable S, is given by the following, where F represents the MCTE coefficient for a specific material and N represents the mass of that material consumed in one year:

$$S = \frac{F_{paper}N_{paper} + F_{steel}N_{steel} + F_{aluminum}N_{aluminum} + F_{glass}N_{glass} + F_{plastics}N_{plastics}}{Total\ Mass\ of\ all\ Recyclable\ Waste\ Produced}\ .$$

The output of this function yields -.5459, which means that .5459 metric tons of carbon emissions were not sent into the atmosphere for every one ton of waste recycled. However, S only accounts for 70.9% of the MCTE savings for all waste generated. We made the assumption that the miscellaneous metal products, textiles, wood, and leather products had a similar recovery rate, because information on the emissions generated through their recycling process is sparse and incomplete, failing to yield a usable number reflecting the benefits of recycling for that specific material. Specifically, to extend this percentage recovery rate, we multiplied by (.79)^-1 to account for the total mass of recyclable waste. The approximate MTCE savings from recycling 1 ton of waste of "average" composition is -.769 MTCE per ton of waste. We assume that this average value will accurately portray the variation of each city's waste to within a negligible margin.

Summary of Testing Each Method

To determine which method of recycling would be the best for each city, two main factors must be considered: the ultimate revenue of the recycling program and its impact on the environment, both extrapolated out to ten years' time in order to examine the efficacy of each method once the programs have had a chance to recover from their initial costs.

The revenues of Methods 1, 2, and 3 for 1 year are given by J_D, J_S, and J_T, respectively, minus the initial cost C. C is defined by $6.8 million for plants that sort materials (as in Methods 2 and 3), and $2.3

million for plants that do not sort materials, as in Method 1 (Recycling Today). These values are able to give us a ballpark estimate of the initial cost to build a recycling plant, but it does not take into account factors such as economic changes that affect the cost of building materials, the fact that different cities have different recycling needs and taxes on land, permits and other associated costs, as well as geographical differences that cause variances in construction costs and transport of materials. However, our assumed initial cost results in the ultimate revenue as given by

$$-C + \sum_{t=3}^{12} J\ ,$$

where t refers to the time in years (which affects population, or $P(t)$), so the revenues from 2013–2022 are added together.

Over ten years, the tons of materials recycled is the sum of each year's recycled total ($M(t)$).The impact on the environment is analyzed by examining the amount of energy saved per ton of materials recycled, a constant X = -0.769. When ultimate tons of waste is multiplied by X, the result is the ultimate energy saved by recycling in terms of carbon emissions for those ten years, which is represented by

$$-0.769 * \sum_{t=3}^{12} M(t)\ .$$

By dividing the ultimate carbon emissions not released into the atmosphere by the ultimate revenue, the result is the amount of carbon emissions saved per dollar spent on recycling for those ten years. The method that corresponds to the biggest "bang for the buck" is the best method for each city (highlighted in boldface in the Summary table).

According to these calculations, Fargo and Wichita would benefit most from single-stream curbside recycling in addition to a trash tax, while Price would benefit most from a drop-off location for pre-sorted recyclables. These differences are due to the stark differences in population—in a very small town like Price, a curbside collection would simply be too inefficient because of high collection costs, while in bigger cities like Fargo and Wichita, the immense revenues generated from the trash tax are enough to outweigh collection costs and the higher initial costs to build a plant that is able to separate materials. In fact, if given five more years, the recycling plants in Fargo and Wichita will actually begin generating positive ultimate revenue (i.e., profits will completely eclipse the high initial costs). Recycling normally costs the plant money, as seen in reports for the recycling plants in Wayne and Susquehanna, PA, but in the cases of Fargo and Wichita, recycling may actually generate money for the industry. The more people that recycle in a given area, the more efficient and profitable recycling becomes.

The advantages of this model is that it accounts for changes in revenue and saved energy over time and is able to compare the two in order to determine the recycling method that is best in terms of both components for each city. However, it compounds the disadvantages of the summed functions (mentioned previously) and may be, in effect, more sensitive to discrepancy.

Summary of Results

Table 2: Method 1 - providing locations where one can drop off pre-sorted recyclables.

	Fargo	Price	Wichita
Ultimate Tons of Waste	310,177	21,007	1,065,751
Metric Tons Carbon per Ton Waste (X)	-0.769	-0.769	-0.769
Ultimate Revenue	-$14,666,756.99	-$3,137,549.09	-$44,791,492.37
Metric Tons of Carbon Saved per Dollar	**.016**	**.005**	**.018**

Table 3: Method 2 - providing single-stream curbside recycling.

	Fargo	Price	Wichita
Ultimate Tons of Waste	310,177	21,007	1,065,751
Metric Tons Carbon per Ton Waste (X)	-.0769	-.0769	-.0769
Ultimate Revenue	-$26,815,721.81	-$8,155,581.71	-$75,572,912.03
Metric Tons of Carbon Saved per Dollar	**.009**	**.002**	**.011**

Table 4: Method 3 - providing single-stream curbside recycling in addition to having residents pay for each container of garbage collected.

	Fargo	Price	Wichita
Ultimate Tons of Waste	359,805.32	24,368.12	1,236,271.16
Metric Tons Carbon per Ton Waste (X)	-.0769	-.0769	-.0769
Ultimate Revenue	-$2,279,567	-$6,802,536.86	-$2,312,767.97
Metric Tons of Carbon Saved per Dollar	**.121**	**.003**	**.411**

Table 5: Summary: Metric Tons of Carbon Saved per Dollar.

	Fargo	Price	Wichita
Method 1	.016	**.005**	.018
Method 2	.009	.002	.011
Method 3	**.121**	.003	**.411**

Recommendations to the EPA

In light of this investigation, it was determined that none of the three proposed recycling programs would be profitable for the government to run a publicly funded recycling plant within the ten-year time frame. To determine which recycling program a city should use, it may determine which program produces that highest ratio of tons of carbon emissions saved through the program divided by the number of dollars the town must fund in order to run the program.

In middle- to large-sized metropolitan areas such as Wichita and Fargo, with ratios of .411 and .121, instituting a program of taxing citizens and collecting commingled recyclables were both most efficient in terms of the carbon-to-dollar ratio. However, upon further extrapolation of the data, utilizing the third method of single-stream recycling with a trash tax in medium- to large-sized cities would eventually become profitable to the government after spanning a 15-year time frame.

In a small town scenario, a recycling plant will never become profitable to the government and overall returns the lowest environmental benefit per taxpayer dollar. Therefore, the best solution for small towns is a pre-sorted drop-off system, the system with the lowest facility process cost. This conclusion is evidenced by the results of the study of Price, Utah, where we determined that the city should adopt the method of drop-off points for sorted recycling material.

It is important to note that the ratios, regardless of the program, generated for small towns are significantly smaller than those for larger urban hubs. Our study found that large cities tend to produce larger ratios, a logical conclusion given that the total amount of decrease in carbon emissions would be compounded in a high density area, meaning larger amounts of waste could be recycled more efficiently. These facts indicate that primacy should be given to regions with the highest populations and ratios because of the total reduction in environmental impact.

Essentially, the evidence acquired in this study shows that no single national recycling program would be most effective in producing the largest reduction in carbon emissions per taxpayer dollar. Instead, allowing local governments to choose among the many options available, some of which were not mentioned in this study, is the ideal solution for ensuring maximum levels of recycling. Therefore, the best way that the EPA can enforce optimal recycling habits in the different regions of the United States is to require these local governments to look into the many options available, and then choose the one that gives them the largest ratio of carbon emissions diverted to government dollar spent.

Conclusion

In conclusion, we determined that the amount of plastic waste generated over the next ten years is 365 million tons, and the amount of plastic waste that will be in an American landfill ranges from 141 to 149 million tons, with the variation due to potential behavior changes in recycling habits.

We also determined that there is not any one-size-fits-all method for recycling; rather, different methods provided a more favorable ratio of environmental benefit to dollar depending on the population of the given town. Therefore, we advise the EPA to create varying regulations based on differences in population. Our general model is strong in that it takes into account changes in population as well as related changes in waste generation. By accounting the costs of implementing each method as well as its environmental impact, this model provides a thorough analysis of what method will produce the most favorable ratio of environmental benefit to cost, instead of being influenced simply by revenue generation. After all, while cost-efficiency analysis is necessary to incorporate economic feasibility, improvement of the environment and a better, cleaner world for the future is our real goal.

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